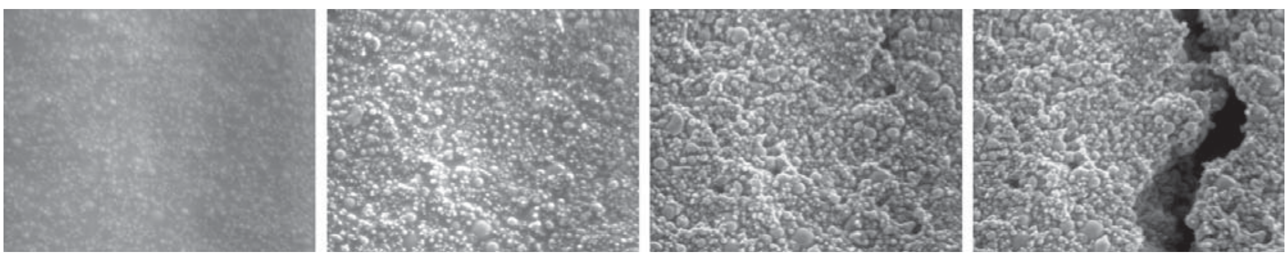
LICENTIATE THESIS

Plastic Shrinkage Cracking in Concrete



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Structural Engineering

Luleå University of Technology

PLASTIC SHRINKAGE CRACKING IN CONCRETE

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Luleå 2016

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Cover photo from Slowik, et al. (2008), shows Scanning Electron Microscope images of the process of plastic shrinkage cracking in drying suspension of fly ash and water (magnification factor 300).The photo is published here with permission from Professor Volker Slowik, Leipzig University of Applied Science (HTWK Leipzig).

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Adj. Prof. Hans Hedlund, Luleå University of Technology

PREFACE

This PhD project, started on September 2013 at the Division of Structural and Fire Engineering of Luleå University of Technology (LTU), aims at investigating the plastic shrinkage cracking phenomenon of fresh concrete. The project was financially supported by the Development Fund of the Swedish Construction Industry (SBUF), to whom I am sincerely grateful.

This licentiate thesis was not to be written without the support and motivations I have received from so many people. In particular, it is a genuine pleasure to acknowledge the efforts of my main supervisor Prof. Mats Emborg, who guided me through this journey by his fruitful advices. His dedication, commitment and overwhelming attitude to help me was the main driving force in this work. Also, special thanks are due to my assistant supervisors Prof. Jan-Erik Jonasson, Adj. Prof. Hans Hedlund and Prof. Andrzej Cwirzen for their support and valuable comments.

I would like to express my deep sense of gratitude to Adj. Prof. Ingemar Löfgren from Chalmers University, for his concern, support and remarkable comments on my work by which my path was enlightened. Furthermore, I should express my thankfulness to Prof. Volker Slowik from Leipzig University of Applied Sciences, for his technical support and productive discussions.

I thank profusely all the technicians of CompLab at Luleå University of Technology for their technical help. Also, I would like to thank all my friends and colleagues at the Division of Structural and Fire Engineering for the fantastic working environment and all the enjoyable moments.

Moreover, no matter how hard I try, I cannot thank my parents enough for all the love, joy, happiness and protection, I received from them during my lifetime. Their sacrifices, dedication and suffering are the main reasons behind any task I accomplish in my life, and for that I am always in their debt.

Last but not least, I would like to express my deep indebtedness and appreciation to my beloved wife, Sally, and my precious little princess, Nicole, who provided all I needed to carry out this task. Without their love, support and motivations, the completion of this project could not have been possible.

Faez Sayahi
Luleå, September 2016

ABSTRACT

Early-age (up to 24 hours after casting) cracking may become problematic in any concrete structure. It can damage the aesthetics of the concrete member and decrease the durability and serviceability by facilitating the ingress of harmful material. Moreover, these cracks may expand gradually during the member's service-life due to long-term shrinkage and/or loading. Early-age cracking is caused by two driving forces: 1) plastic shrinkage cracking which is a physical phenomenon and occurs due to rapid and excessive loss of moisture, mainly in form of evaporation, 2) chemical reactions between cement and water which causes autogenous shrinkage. In this PhD project only the former is investigated.

Rapid evaporation from the surface of fresh concrete causes negative pressure in the pore system. This pressure, known as capillary pressure, pulls the solid particles together and decreases the inter-particle distances, causing the whole concrete element to shrink. If this shrinkage is hindered in any way, cracking may commence. The phenomenon occurs shortly after casting the concrete, while it is still in the plastic stage (up to around 8 hours after placement), and is mainly observed in concrete elements with high surface to volume ratio such as slabs and pavements.

Many parameters may affect the probability of plastic shrinkage cracking. Among others, effect of water/cement ratio, fines, admixtures, geometry of the element, ambient conditions (i.e. temperature, relative humidity, wind velocity and solar radiation), etc. has been investigated in previous studies. In this PhD project at Luleå University of Technology (LTU), in addition to studying the influence of various parameters, effort is made to reach a better and more comprehensive understanding about the cracking governing mechanism. Evaporation, capillary pressure development and hydration rate are particularly investigated in order to define their relationship.

This project started with intensive literature study which is summarized in Papers I and II. Then, the main objective was set upon which series of experiments were defined. The utilized methods, material, investigated parameters and results are presented in Papers III and IV.

It has been so far observed that evaporation is not the only driving force behind the plastic shrinkage cracking. Instead a correlation between evaporation, rate of capillary pressure development and the duration of dormant period governs the phenomenon. According to the results, if rapid evaporation is accompanied by faster capillary pressure development in the pore system and slower hydration, risk of plastic shrinkage cracking increases significantly.

Key words: Plastic shrinkage cracking, Evaporation, Capillary pressure, Hydration rate.

SAMMANFATTNING

Tidig sprickbildning (upp till 24 timmar efter gjutning) kan bli problematiskt i betongelement. Den kan skada de estetiska egenskaperna hos betongelementet och minska hållbarheten och servicevänlighet genom att underlätta inträngning av skadliga material. Dessutom kan dessa sprickor expandera successivt under betongens livslängd på grund av långsiktig krympning och/eller lastning. Tidig sprickbildning orsakas av två drivkrafter: 1) plastisk krympsprickbildning som är ett fysikaliskt fenomen och uppstår på grund av en snabb och stor förlust av fukt, främst i form av avdunstning, 2) kemiska reaktioner mellan cement och vatten som orsakar autogen krympning. I detta doktorandprojekt undersöks endast den förstnämnda.

Snabb avdunstning från ytan av färsk betong förorsakar undertryck i porsystemet. Detta tryck, känt som kapillära undertrycket, drar de fasta partiklarna tillsammans och minskar avståndet mellan dem, vilket gör att hela betongelementet krymper. Om denna krympning hindras på något sätt, påbörjar sprickbildning. Detta fenomen som inträffar kort efter gjutning av betongen, medan den fortfarande är i plastiskt skede (upp till ca 8 timmar efter gjutning), är i huvudsak observerat i betongkonstruktioner med hög yta till volymförhållande såsom plattor, industrigolv, beläggningar och brobanor.

Många parametrar kan påverka sannolikheten för plastisk krympsprickbildning. Bland annat har effekten av vatten/cement-tal (vct), finmaterial, tillsatsmedel, geometri av elementet, omgivningsförhållanden (dvs. temperatur, relativ fuktighet, vindhastighet och solinstrålning), etc. undersökts i tidigare studier. Under detta doktorandprojekt vid LTU, förutom att studera inverkan av olika parametrar, har ansträngningar gjorts för att nå en bättre och mer omfattande förståelse om sprickbildning styrande mekanism. Avdunstning, utveckling kapillära undertryck och hydratiseringshastigheten har särskilt undersökts för att definiera deras inbördes förhållande att påverka sprickbildningen.

Projektet började med en intensiv litteraturstudie som sammanfattas i artiklar I och II. Därefter definierades det huvudsakliga målet och experimentupplägg. De använda metoderna, material, undersökta parametrar och resultaten presenteras i artiklar III och IV.

Det har observerats i studien att avdunstningen inte är den enda drivkraften bakom plastisk krympsprickbildning. Istället styrs fenomenet genom en korrelation mellan avdunstning, hastigheten för kapillära undertryck utveckling och hydratiseringshastigheten. Enligt resultaten ökar risken för plastisk krympsprickbildning betydligt.om snabb avdunstning sker samtidigt som en snabb kapillär tryckutveckling i porsystemet samt långsam hydratation,

Nyckelord: plastisk krympsprickbildning, avdunstning, kapillära undertryck, hydratationshastigheten.

TABLE OF CONTENTS

NOTATIONS

Symbol	Description	Unit
E	water evaporation rate	[lb/ft^2/hr], [kg/m^2/h]
e_0	pressure of saturated vapour	[psi]
e_a	vapour pressure of the ambient air	[psi]
M_w	molar mass of water	[kg/mol]
P	pressure	[Pa]
P_c	capillary pressure	[Pa]
R	radius of meniscus when wetting angle is zero	[m]
R	ideal gas constant	[J/mol K]
$R´$	radius of meniscus for an arbitrary wetting angle	[m]
RH	relative humidity	[%]
r	relative humidity	[%]
S	specific surface area	[m^2/kg]
T	absolute temperature	[K]
T_a	air temperature	[°F], [°C]
T_c	concrete temperature	[°F], [°C]
V	wind speed	[mph]
W	water evaporation rate	[lb/ft^2/hr]
w/c	water/cement ratio	[weight%]
w/b	water/binder ratio	[weight%]
γ	surface tension of the pure liquid	[N/m][J/m^2]
γ_w	surface tension of the pure liquid	[N/m]
ρ_w	density of water	[kg/m^3]

Abbreviation	Description
ACC	accelerator
C	cement
CPSS	capillary pressure sensors system
CRR	cracking reduction ratio
FRC	fibre-reinforced concrete
HPC	high-performance concrete
SCC	self-compacting concrete
SP	superplasticizer
SRA	shrinkage-reducing admixture
UHPC	ultra high-performance concrete
W	water

Part I

1. INTRODUCTION

1.1 Background

Early-age shrinkage in concrete may lead to deleterious cracking which in some occasions can dramatically impair the aesthetics, durability and serviceability of a structure (Boshoff & Combrinck 2013, Sivakumar & Santhanam 2006). Plastic- and autogenous shrinkage are the two main phenomena by which early-age shrinkage is caused. The former occurs due to excessive loss of water e.g. by evaporation, whereas the latter is a result of hydration and chemical reactions (Sivakumar & Santhanam 2006).

Plastic shrinkage and its probable cracking, the main topic of this research, occurs shortly after casting, while the concrete still is in its plastic phase, Figure 1.1. The phenomenon is defined as the shrinkage of young concrete which occurs due to rapid and excessive drying. The cracking occurs when the concrete surface dries and shrinks so fast, that the induced tensile strains exceed the strain capacity of the very young concrete. It may clearly affect the aesthetics, durability and serviceability of the structure by accelerating the ingress of harmful materials that might cause damage in future, e.g. corrosion of the reinforcement.

According to ACI 305R (1999): “Plastic shrinkage cracking is frequently associated with hot weather concreting in arid climates. It occurs in exposed concrete, primarily in flat work but also in beams and footings and may develop in other climates whenever the evaporation rate is greater than the rate at which the water rises to the surface of recently placed concrete by bleeding”. The main driving force behind the phenomenon is thus believed to be rapid and excessive loss of water, which mainly takes place in form of surface water evaporation.

Figure 1.1 - Plastic shrinkage cracking at concrete surface from Slowik, et al. (2008).

However, this description is more suitable for conventional concretes where a thin layer of water covers the surface due to bleeding (Schmidt & Slowik 2013). In concretes of lower water/cement ratios (w/c) and those including considerably high volumes of fines, like self-compacting concrete (SCC), where the bleeding rate is very low and other types of water loss (e.g. suction of water by the fine material) take place in addition to evaporation. In other words, water does not accumulate on the SCC surface (Esping 2007).

Plastic shrinkage cracking mainly occurs in horizontal concrete elements with large surface to volume ratio (e.g. slabs, pavements, industrial floors). As a result of water evaporation, hydraulic pressure (capillary pressure) builds-up in the pore system which in turn causes the concrete to shrink (Lerch 1957, Ravina & Shalon 1968, Van Dijk & Boardman 1971, Kasai, et al. 1972, Cohen, et al. 1990, Radocea 1992, Almusallam, et al. 1999, ACI 1999, Qi, et al. 2003, Josserand, et al. 2006, Dao, et al. 2010, Schmidt & Slowik 2013, Uno 1998). If the concrete is restrained (e.g. by the formwork, reinforcement, change of sectional depth, difference in shrinkage in different parts of the concrete, etc.) and it has not gained enough tensile strength, the shrinkage will lead to cracking.

Unlike autougenous shrinkage induced cracks which usually propagate uniformly through the concrete member, plastic shrinkage cracks initiate at the concrete surface and develop inward. These cracks often are formed in meshed or parallel patterns. They usually are between 50 mm to 1000 mm long and up to 2 mm wide with 50 mm to 700 mm crack spacing (Kosmatka, et al. 2002). However, sometimes these cracks can be such fine that may not be detected by unaided eye. They can propagate deep into the concrete element and even through the entire cross-section (Slowik, et al. 2008).

Many parameters may influence the cracking tendency of concrete at its early age. Among others, w/c ratio, type of cement, fibres, admixture, member size, fines content, temperature of the concrete surface and ambient conditions (i.e. relative humidity, air temperature and wind velocity) may increase or decrease the risk of cracking (Uno 1998, Boshoff & Combrinck 2013, Lura, et al. 2007).

The risk of plastic shrinkage cracking has increased during the past few decades. Nowadays, in commonly used concretes, such as high performance concrete (HPC), ultra-high performance concrete (UHPC) and self-compacting concrete (SCC), early-age cracking can be highly problematic, as they possess large shrinkage after casting. The reason lies into the fact that these concretes have relatively low water/binder (w/b) ratio and contain high dosage of water-reducing admixture (superplasticizer). This phenomenon, thus, is not limited only to hot and arid countries and has become a challenge even in the cold Scandinavia. How serious plastic shrinkage cracking in these kind of concretes is, can be comprehended in Kompen's (1994) final remarks in his internal report about a bridge construction project in Norway (Hammer 2007):

> *"The plastic cracking phenomenon is regarded the most serious problem met in using low w/b-ratio concrete. There are serious worries that this phenomenon will jeopardise the quality improvements intended by the use of low w/b concretes. By observation in the field and full-scale trials a lot of experience has been gained on how to reduce cracking to a more acceptable level. Understanding of the mechanisms involved has, however, not reached such a level that this cracking can be completely avoided in every construction work. Consequently, it is strongly recommended that research should continue on*

> *early age cracking problem, to develop both basic understanding and practical measures."*

The research performed in Scandinavia on plastic shrinkage cracking can be traced back to mid-1980s. Researchers such as Hedin (1985), Radocea (1992), Johansen and Dahl (1993), Hammer (1999), Esping and Löfgren (2005) and engineering students as Lund et al. (1997) studied different aspects of plastic shrinkage cracking and prepared a strong launch platform for further investigations (Sayahi, et al. 2014, Paper I).

Despite of the lack of consensus about a generally accepted theory, what seems to be important based on these studies, is to distinguish between the cracking mechanisms which are driven by the loss of moisture (i.e. plastic shrinkage) and those which are caused by hydration and chemical reactions (i.e. autogenous shrinkage).

Once the cracking mechanism is identified at the planning stage or during casting, proper measures can be applied in order to reduce the cracking risk at the very initial phase. For instance if the concrete is considered susceptible to plastic shrinkage cracking, reducing the amount of the transferred moisture to the environment by using appropriate curing measures can be effective. Furthermore, a proper mix design (e.g. adding shrinkage-reducing admixture) may reduce the plastic and autogenous shrinkage of the concrete (Lura, et al. 2007).

In general, early-age cracking in concrete is a result of complex relationship between interconnected parameters such as evaporation, capillary pressure, hydration rate, settlement, etc. Gaining a comprehensive understanding about the phenomenon requires a high level of persistence and intense theoretical and experimental investigation. Having such knowledge may facilitate the identification of the early-age shrinkage components (i.e. plastic- and autogenous shrinkage) and accordingly the proper crack preventative measure.

1.2 Hypothesis, aim and research questions

Based on above the following hypothesis, aim and research questions can be formulated:

Hypothesis: Evaporation is not the only driving force behind plastic shrinkage cracking. Instead a complex correlation between several parameters (e.g. evaporation, capillary pressure, hydration rate, etc.) governs the phenomenon.

Aim: The project aims at gaining more knowledge about the early-age behaviour of concrete in general. Comprehending the governing mechanism behind the early-age cracking, especially in the plastic stage, is particularly of interest. The final outcome is intended to be a collection of pre- and post-casting measures which form a general guideline to prevent or reduce the risk of plastic shrinkage cracking in young concrete.

Research questions: The research is adapted and formulated in order to find answers of the following questions:

RQ1 – Is water evaporation really the main reason behind plastic shrinkage cracking of young concrete?

RQ2 – What is the role of capillary pressure in the cracking process?

RQ3 – In which way are vertical and horizontal deformation related to other influencing factors (i.e. evaporation, capillary pressure and hydration rate)?

RQ4 – Can the effects of parameters related to mix design as well as to ambient conditions at casting be graded and quantified individually.

1.3 Limitations

The presented research is confined due to several limitations. First, the vast domain of various parameters that may affect the early-age cracking of concrete makes it really hard to examine and identify the effect of each. Therefore, a limited number of factors, which were considered the most important, were chosen to be tested.

The second limitation lies in the interconnected nature of the concrete mixture's constituents. It is almost impossible to modify the amount of one constituent, without substituting, adding and/or adjusting others, which makes it difficult to study the pure effect of a particular constituent.

The third limitation is the dissimilar moisture loosing mechanisms of different concrete types. While in conventional concrete, the moisture is mostly lost due to evaporation of the surface water, in other types of concrete such as SCC, HPC and UHPC, the water is partially absorbed by the fine material. However, in order to have a standard procedure for all the experiments, it is assumed that the loss of water occurs only due to evaporation.

1.4 Scientific approach

This study commenced by an intensive literature review which included books, papers and technical reports about various topics that are related to the early-age behaviour of concrete in one way or another. This vast set of references included papers from 1941 and onwards. The information collected at this stage revealed the gaps and the neglected aspects of the topic, which needed to be covered. Furthermore, the research questions were raised based on the identified knowledge gaps. The information collected are summarized and presented in a state of the art journal paper.

According to the literature, early-age cracking, as already mentioned, is caused by two different mechanisms:

- Loss of moisture, mainly due to evaporation (plastic shrinkage)
- Chemical reactions which lead to autogenous shrinkage.

Furthermore, it was observed in literature that the influence of capillary pressure in the pore system, somehow, was underestimated, if not neglected. Even if the role of capillary pressure was investigated, the results did not look logical in the studied papers and technical reports, due to inaccurate measurements and/or inappropriate measuring techniques. Consequently, the relationship between evaporation and capillary pressure, if there is any, has not clearly been determined.

The fundamental scientific approach of this project, thus, is based on separating the early-age cracks based on their governing mechanisms and identifying the relationship between evaporation and capillary pressure. This relationship can be further expanded to include the internal temperature evolution (i.e. hydration rate) by which the different structural phases of concrete can be determined (see Section 2.1).

Qualitative and quantitative studies were conducted in form of series of laboratory tests, in which the hypothesis was tested and the research questions were addressed. Three experimental setups (i.e. rectangular mould, ASTM C 1579 and NORDTEST method) were utilized during the tests. Each setup was modified to some extent in order to include more measurements and/or increase the accuracy.

During the tests, water evaporation, capillary pressure, hydration, settlement and horizontal deformation (i.e. shrinkage) were recorded. The outcomes of the laboratory tests are then intended to be compared with the results of half- and full-scale field tests. The experimental results, alongside with the information collected at the literature review stage, has led to conclusions and crack preventative measures, which are reported in this thesis and the appended papers.

1.5 Disposition of the thesis

This licentiate thesis summarizes the outcomes of the first three years of a PhD project at Luleå University of Technology which investigates the plastic shrinkage cracking in young concrete. The thesis consists of 5 chapters which are briefly described below:

Chapter 1 generally describes the conducted research trough presenting background, aim and the scientific approach followed in the project.

Chapter 2 explains the mechanism of the early-age concrete deformation and the main factors affecting plastic shrinkage cracking.

Chapter 3 describes the experimental methods and measuring techniques utilized in the study, by which plastic shrinkage cracking in fresh concrete is investigated.

Chapter 4 presents the results and the findings of the experimental work performed by methods explained in Chapter 3.

Chapter 5 concludes the thesis based on the findings and addresses the research questions raised initially.

1.6 Appended papers

<u>*Paper I*</u>

> *”Plastic Shrinkage Cracking in Concrete: Research in Scandinavia”*, **Sayahi, F.**, Emborg, M. and Hedlund, H. (2014), published in proceeding of the XXII Nordic Concrete Research symposium, Reykjavik, Iceland, August 13 – 15, 2014, pp. 351 – 354.

The paper briefly describes the research that has been carried out on plastic shrinkage cracking in concrete in Scandinavia. Besides, the first laboratory test plan and future work are presented.

Paper II

"Plastic Shrinkage Cracking in Concrete: State of the Art", **Sayahi, F.**, Emborg, M. and Hedlund, H. (2014), published in Nordic Concrete Research, Vol. 51, No. 3, December 2014, pp. 95 – 110.

Paper II presents a state of the art in which research from all around the world are summarized. Mechanism of plastic shrinkage cracking is explained and the roles of various parameters (evaporation, bleeding and capillary pressure) are defined. In addition, effect of various factors (e.g. w/c ratio, depth of the element, additives, fibres, fines content and post-casting curing measures) is briefly discussed.

Paper III

"Plastic Shrinkage Cracking in Self-Compacting Concrete: a Parametric Study", **Sayahi, F.**, Emborg, M. and Hedlund, H. Löfgren, I. (2016), published in proceeding of the international RILEM conference on Materials, Systems and Structures in Civil Engineering, MSSCE 2016, Lyngby, Denmark, August 22 – 24, 2016, pp. 609 – 619.

The conference paper reports the results of laboratory experiments performed using ring test method. Influence of w/c ratio, cement type, coarse aggregate content and SP on the early-age cracking of SCC is investigated in this paper. The results are presented in form of evaporation, capillary pressure, internal temperature and average crack area measurements. The findings of these experiments form the basis of the theory presented in Paper IV.

Paper IV

"The Relationship between Evaporation, Capillary Pressure and Dormant Period during Plastic Shrinkage Cracking of Self-Compacting Concrete", **Sayahi, F.**, Emborg, M. and Hedlund, H. (2016), ready for submission.

In Paper IV, the experimental results presented in Paper III, are utilized in order to explain a theory about the relationship between evaporation, rate of capillary pressure development and rate of hydration (i.e. duration of dormant period) of SCC. Effort is made to distinguish between the plastic- and the autogenous shrinkage induced cracking.

2. PLASTIC SHRINKAGE IN CEMENTITIOUS MATERIAL

2.1 Introduction

The total shrinkage that any concrete element experiences during its lifespan is, as known, caused by various contracting mechanisms. Among others, phenomena such as evaporation, hydration and/or carbonation can participate in the total shrinkage of the cementitious materials (Esping 2007). However, the effect of these phenomena on the concrete's total shrinkage is strongly time-dependent and hence, the total shrinkage of concrete can be divided into: (a) early-age shrinkage which represents the shrinkage in the first 24 hours after mixing, and (b) long-term shrinkage for the time beyond (Esping 2007). Figure 2.1 illustrates the governing mechanisms of the total shrinkage in cementitious materials and the way they influence the early-age and long-term shrinkage. It ought to be noted that long-term shrinkage is not the topic of this research. Instead, early-age shrinkage and its driving mechanisms (especially plastic shrinkage) are particularly investigated.

As mentioned, early-age shrinkage consists of plastic and autogenous shrinkage. Distinguishing these two shrinkage mechanisms is the key in choosing the appropriate crack preventative measure in concrete's initial phase.

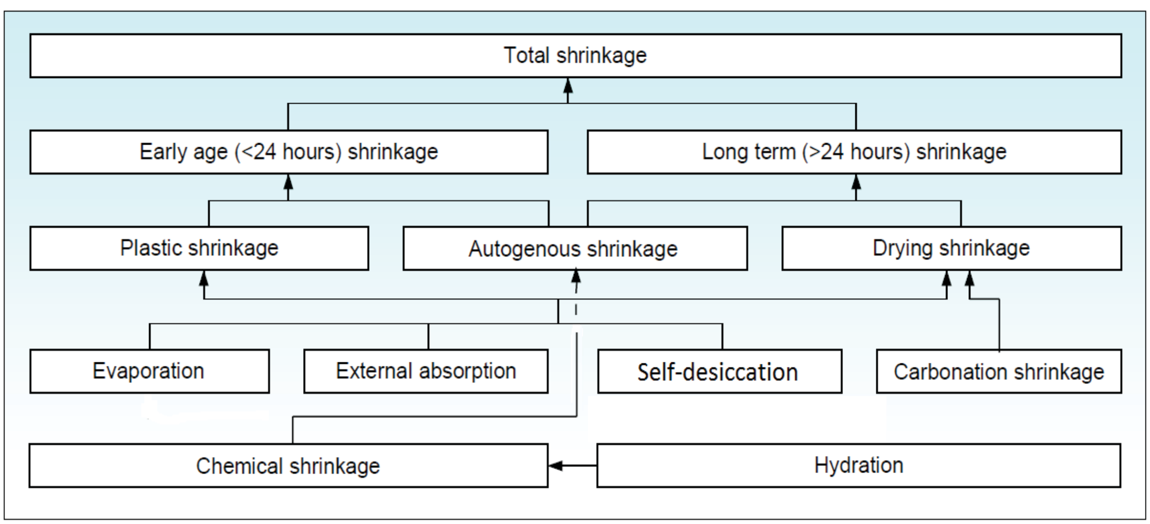

Figure 2.1. Illustration of the governing mechanisms of the total shrinkage in cementitious materials, based on Esping (2007).

In literature (Holt 2001, Esping 2007), it is concluded that the fresh concrete experiences three different structural phases (states) in the first 24 hours after mixing:

1- *Plastic*: the concrete at this stage is still liquid, plastic, viscoelastic and workable.

2- *Semi-plastic*: commences after the initial setting, where a stiff skeleton starts to form and the concrete gradually becomes rigid.

3- *Rigid*: begins after the point of final setting. At this stage the maximum hydration heat is probably reached and the strength of the concrete increases due to the ongoing hydration.

Due to the chemical reaction between the cement and water, a self-load bearing skeleton forms inside the concrete which leads to solidification of the mixture. Initial setting of the concrete is defined as the border between the plastic and semi-plastic phases, where the solidification begins. Up to this point, the concrete is still workable and fluid. On the other hand, final setting of the concrete is reached when the mixture passes from the semi-plastic state to the rigid phase. By then, the concrete is stiff enough to carry its own weight and support stresses. However, determining the exact time of the initial and final set is not possible since neither is a distinct and well-defined physical state (Esping 2007).

There are several methods for determining the time of initial and final setting such as Vicat needle (EN 196-3), the penetration resistance method (ASTM C403) and the ultrasonic technique (De Haas, et al. 1975, Reinhardt, et al. 2000, Esping 2007). However, the settings time is usually defined arbitrarily according to the deformation and/or the hydration heat development rate, see Figure 2.2.

The period of plastic shrinkage is defined from mixing until the final setting i.e. sum of the plastic and the semi-plastic phase of the concrete (Tattersall & Banfill 1983, Mindess, et al. 2003, Neville 1995). However, since no significant chemical reaction takes place in the plastic stage (i.e. before the initial set), it is assumed that the governing mechanism at this phase is predominantly physical (i.e. evaporation). In this study, the term "plastic shrinkage" is used only for describing this physical process that leads to early-age cracking. Meanwhile, the shrinkage originating from chemical reactions and mainly occurring after the initial setting is referred as autogenous shrinkage.

Figure 2.2 illustrates the relationship between the rate of hydration heat development, early-age deformation and the setting times (initial and final) of the concrete mixture in the first 24 hours after mixing in experiments performed by Esping and Löfgren (2005). What is ought to be noted here is the period between mixing and the initial set, which is known as dormant period. During this period the hydration rate is very low. Accordingly, the cracking mechanism at this stage is totally physical and induced by loss of water, mainly due to evaporation. The duration of dormant period, thus, may facilitate the separation between the plastic shrinkage cracks and those caused by autogenous shrinkage.

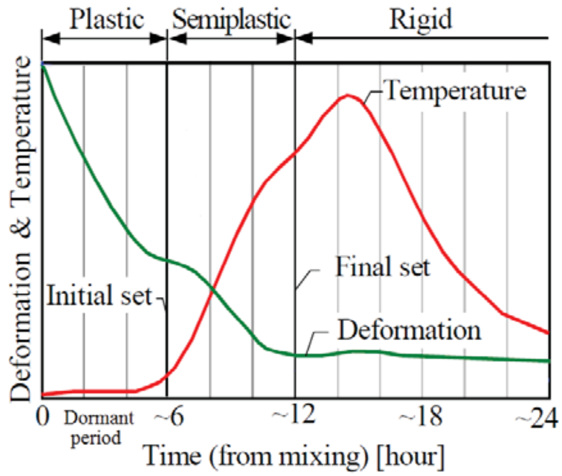

Figure 2.2 - Illustration of the three structural phases of concrete vs. autogenous shrinkage and hydration heat evolution in experiments performed by Esping and Löfgren, based on Esping & Löfgren (2005).

2.2 Mechanism of plastic shrinkage

Rapid loss of moisture, mainly due to evaporation dries the concrete surface and makes it shrink easily, as it has poorly developed stiffness. Another crucial parameter influencing the phenomenon is the strain capacity of the concrete. Several experiments (Kasai, et al. 1972, Hannant, et al. 1999, Branch, et al. 2002, Swaddiwudhipong, et al. 2003, Holt & Leivo 2004, Dao, et al. 2009, Morris & Dux 2010) have shown that the strain capacity reaches its lowest value around the initial setting time, Figure 2.3. If the concrete is restrained in anyway (e.g. by the mould, reinforcement, change of sectional depth, difference in shrinkage in different parts of the concrete, etc.), tensile stresses arise at the concrete surface, which eventually may exceed the low strain capacity and cause cracking.

Figure 2.4, in details, illustrates the process of plastic shrinkage cracking in fresh concrete. For conventional concrete, once it is placed in the mould, its solid particles settle under the influence of the gravitational forces, forcing the water in the pore system up to the surface (i.e. bleeding). Consequently, the entire concrete surface is covered with a thin layer of water, as stated by Slowik and Schmidt (2008). However, for self-compacting concrete (SCC) and concrete with low w/b ratio, more or less no free water will accumulate at the surface.

At this stage an inter-connected pore system forms inside the mixture, which is almost completely water-filled. Meanwhile loss of water takes place mainly due to evaporation or in some cases also due to external absorption (i.e. by the mould) and/or self-desiccation. As soon as the rate of evaporation exceeds the rate at which water is transported to the surface (i.e. bleeding), the water layer disappears. Consequently, due to adhesive forces and surface tension, water menisci are formed in the pores (Esping 2007). This is the onset point of negative pressure (capillary pressure) build-up in the concrete pore system, see Paper II and Section 2.4 where the capillary pressure and its development process are further discussed.

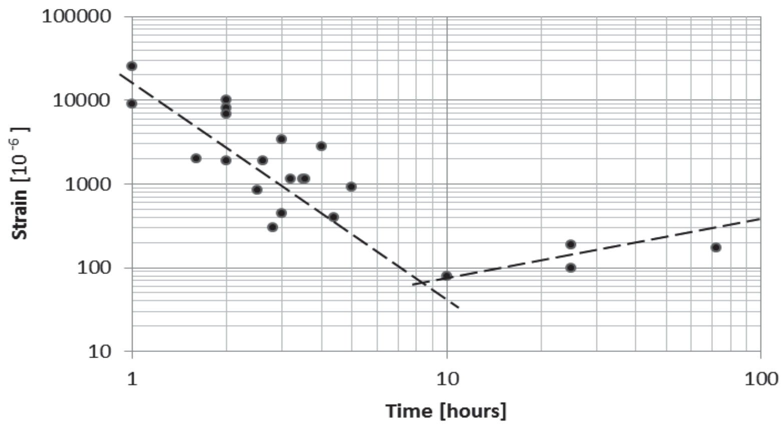

Figure 2.3 - Tensile strain capacity of fresh concrete, based on Boshoff & Combrinck (2013).

The negative pressure then pulls the solid particles together, resulting in shrinkage of the still plastic concrete. Accordingly, the inter-particle spaces become smaller and the pores get narrower which leads to more water drainage to the concrete surface (Slowik, et al. 2008). The progressive evaporation gradually decreases the radius of the menisci resulting in further negative capillary pressure build-up (see Paper II). The capillary pressure in turn causes more settlement by pulling the solid particles down and forcing the pore water to the surface (Lura, et al. 2007). The consolidation together with continues water loss due to the progressive capillary pressure reduces the concrete fluidity before the cement hydration starts (Leemann, et al. 2014). Finally, the solid skeleton is stiff enough to resist the gravitational forces, which means that the vertical deformation (settlement) of the concrete either stops completely or continues with a much lower rate (see Paper II).

Eventually, the menisci can no longer bridge the pore which means that its radius has reached the “break-through” value (minimum possible radius) (Slowik & Schmidt 2010). The capillary pressure suddenly breaks down and the pores are no longer completely filled with water (Slowik & Schmidt 2010). This facilitates air penetration in the pore system starting from the largest pores. Therefore, this moment is also denoted as air-entry time.

The empty pores form weak points at the concrete surface which are the origin of strain localization. If the shrinkage is hindered, it can lead to cracking, initiating from these empty pores. The cracks form initially at the surface and propagate downwards. This phenomenon can be clearly seen in Figure 2.5 (from left to right), where a suspension made of fly ash and water is subjected to drying. In the first image on the left, the solid particles at the surface are completely covered by a thin layer of water. However, it can be seen in the second image that this layer starts to disappear, due to evaporation. At this point the evaporation is taking place inside the pore system, causing capillary pressure development. The dark dots in the third image are the pores which are penetrated by air after the capillary pressure break-through point. Finally, in the fourth image, these empty pores are connected and have formed a crack (Slowik, et al. 2008).

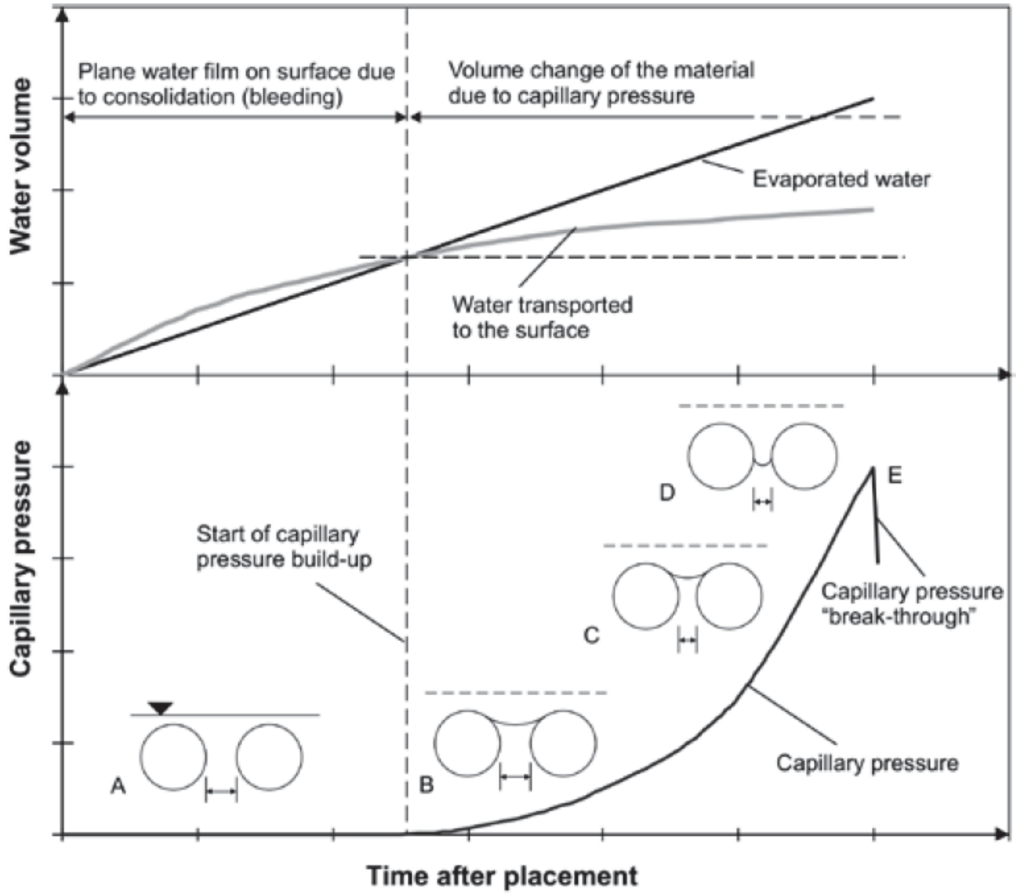

Figure 2.4- Mechanism of capillary pressure build-up and the consequent plastic shrinkage in concrete, from Schmidt & Slowik (2013)

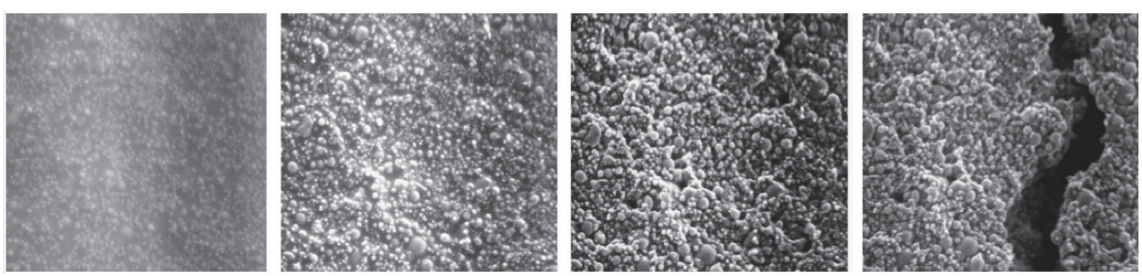

Figure 2.5 – Scanning Electron Microscope images of drying suspension of fly ash and water, magnification factor 300, from Slowik, et al. (2008).

Despite of the fact that plastic shrinkage cracking is mainly related to the evaporation rate of the concrete, the role of capillary pressure in the governing mechanism of plastic shrinkage cracking is also pronounced by several researchers ((Uno 1998, Schmidt &Slowik 2013, Boshoff & Combrinck 2013, Radocea 1994). Evaporation and capillary pressure are further discussed in the following sections.

2.3 Evaporation

As evaporation has been considered a plastic shrinkage cracking probability indicator in fresh concrete, focus has been on this specific parameter in concrete technology. According to ACI, precautions must be taken when the water evaporation rate is equal to or more than 1.0 $kg/m^2/h$ (ACI 1999). Nevertheless, some experimental results show that this value may be too high for some modern concrete compositions, i.e. plastic shrinkage cracking may occur at evaporation rate of 0.2 $kg/m^2/h$ under hot weather conditions (Almusallam, et al. 1999).

Water evaporation occurs due to a) heat energy absorption into the water, e.g. air temperature, concrete temperature, solar radiation; b) low humidity, i.e. the ambient pressure is less than that in the water (Uno 1998, Sayahi, et al. 2014). Accumulation of escaping water molecules above the water surface increases the humidity and consequently decreases the evaporation, especially when the concrete perimeter is closed. Thus, wind can accelerate the process as it removes the escaping water molecules.

As can be comprehended from above, the environmental factors that can highly influence the water evaporation rate are air temperature, concrete (water surface) temperature, wind and relative humidity. These factors are used in the ACI nomograph for estimating the rate of surface water evaporation in concrete (see Figure 2.6). The outcome of this nomograph is thus assumed to give a value for the evaporation rate of the concrete, providing an indication of the possible onset of plastic shrinkage cracking (Uno 1998). The nomograph was first developed by Bloem (1960) who in turn used the numerical values presented in a table by Lerch (1957). The values in the table were derived using a formula presented by Menzel (1954) only available in imperial unit system:

$$W = 0.44(e_0 - e_a)(0.253 + 0.096\,V) \qquad (2.1)$$

where:
W = weight (lb) of water evaporated per square foot of surface per hour ($lb/ft^2/hr$),
e_0 = pressure of saturated vapour at the temperature of the evaporating surface, (psi)
e_a = vapour pressure of the ambient air, (psi)
V = average horizontal wind speed at 20 inches (500 mm) above the concrete surface, (mph).

In 1998, based on Menzel's formula, Uno (1998) proposed a single operation equation to predict the water evaporation rate. The new formula does not use vapour pressure as input since a temperature-vapour pressure relationship has already been incorporated in the formula. The correlation coefficient of this relationship is 0.99 for the temperature range 15 to 35˚C (59 to 95 ˚F) (Uno 1998). The formula is expressed as Eq.2.2 (imperial units) and Eq.2.3 (metric units):

$$E = (T_c^{2.5} - r.T_a^{2.5})(1 + 0.4V)\times10^{-6} \qquad (2.2)$$

where
E = water evaporation rate, ($lb/ft^2/hr$)
T_c = concrete (water surface) temperature, (˚F)
T_a = air temperature, (˚F)
r = relative humidity, (%)
V = wind velocity, (mph).

$$E = 5([T_c + 18]^{2.5} - r \, . \, [T_a + 18]^{2.5})(V + 4) \times 10^{-6} \tag{2.3}$$

where
E = water evaporation rate, (kg/m^2/h)
T_c = concrete (water surface) temperature, (˚C)
T_a = air temperature, (˚C)
r = relative humidity, (%)
V = wind velocity, (km/h).

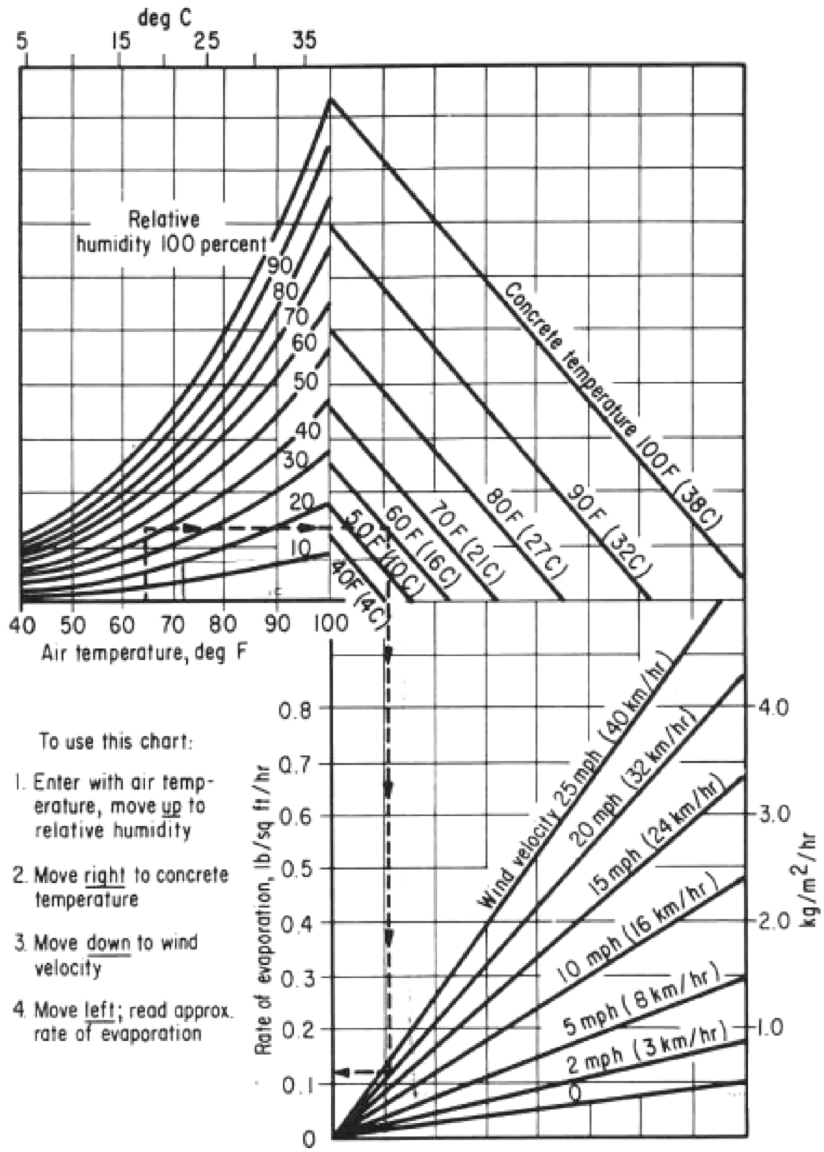

Figure 2.6 – ACI nomograph for estimating surface water evaporation rate of concrete i e. the "ACI Hot Weather Concreting Evaporation Nomograph", from ACI (1999).

Uno's formula and ACI nomograph are widely used since the establishment, due to their simplicity. Comparison between Menzel and Uno's formula shows almost complete accordance in the results. Table 2.1, shows the evaporation rate calculated by Menzel and

Uno's formulas for various atmospheric conditions (e.g. increasing the wind speed, decreasing the RH, increasing the concrete and air temperature, decreasing air temperature, cold air with high RH and wind, cold air and variable wind, average weather conditions, high concrete and air temperature with low RH). As can be seen in the last two columns, the calculated evaporation rate values by the two formulas are very close. In addition both formulas give almost similar evaporation rates to those extracted from the ACI nomograph.

Table 2.1 - Comparison of evaporation rates calculated by Menzel and Uno's formulas, based on Uno (1998).

Group	Condition	Case	Concrete temperature, C (F)	Air temperature, C (F)	Relative humidity, percent	Wind speed, kph (mph)	Evaporation Eq.(2.1)Menzel, kg/m^2/hr (lb/ft^2/hr)	Evaporation Eq. (2.3) [Eq. (2.2)] Uno, kg/m^2/hr (lb/ft^2/hr)
1	Increase wind speed	1	21 (70)	21 (70)	70	0 (0)	0.07 (0.015)	0.06 (0.012)
		2				8 (5)	0.19 (0.038)	0.17 (0.036)
		3				16 (10)	0.30 (0.062)	0.28 (0.061)
		4				24 (15)	0.42 (0.085)	0.40 (0.086)
		5				32 (20)	0.54 (0.110)	0.51 (0.110)
		6				40 (25)	0.66 (0.135)	0.63 (0.135)
2	Decrease relative humidity	7	21 (70)	21 (70)	90	16 (10)	0.10 (0.020)	0.09 (0.20)
		8			70		0.30 (0.062)	0.28 (0.061)
		9			50		0.49 (0.100)	0.47 (0.102)
		10			30		0.66 (0.135)	0.66 (0.143)
		11			10		0.86 (0.175)	0.85 (0.184)
3	Increase concrete temperature and air temperature	12	10 (50)	10 (50)	70	16 (10)	0.13 (0.026)	0.12 (0.026)
		13	16 (60)	16 (60)			0.21 (0.043)	0.20 (0.041)
		14	21 (70)	21 (70)			0.30 (0.062)	0.28 (0.061)
		15	27 (80)	27 (80)			0.38 (0.077)	0.41 (0.085)
		16	32 (90)	32 (90)			0.54 (0.110)	0.53 (0.115)
		17	38 (100)	38 (100)			0.88 (0.180)	0.70 (0.150)
4	Decrease air temperature	18	21 (70)	27 (80)	70	16 (10)	0.00 (0.000)	0.00 (0.004)
		19		21 (70)			0.30 (0.062)	0.28 (0.061)
		20		10 (50)			0.60 (0.125)	0.66 (0.143)
		21		–1 (30)			0.81 (0.165)	0.87 (0.187)
5	Cold air high RH and wind	22	27 (80)	4 (40)	100	16 (10)	1.00 (0.205)	1.13 (0.235)
		23	21 (70)				0.63 (0.130)	0.72 (0.154)
		24	16 (60)				0.35 (0.075)	0.45 (0.088)
6	Cold air and variable wind	25	21 (70)	4 (40)	50	0 (0)	0.17 (0.035)	0.17 (0.035)
		26				16 (10)	0.79 (0.162)	0.84 (0.179)
		27				40 (25)	1.75 (0.357)	1.84 (0.395)
7	Average weather conditions	28	27 (80)	21 (70)	50	16 (10)	0.86 (0.175)	0.88 (0.183)
		29	21 (70)				0.49 (0.100)	0.47 (0.102)
		30	16 (60)				0.22 (0.045)	0.20 (0.036)
8	High concrete and air temperature + low RH	31	32 (90)	32 (90)	10	0	0.34 (0.070)	0.32 (0.069)
		32				16 (10)	1.64 (0.336)	1.60 (0.345)
		33				40 (25)	3.58 (0.740)	3.50 (0.760)

Table 2.2, compares the evaporation rate at 1 hour after casting, measured during the tests performed in this study on conventional concrete, with the outcomes of Uno's formula and ACI nomograph, when $T_a = T_c = 21^{\circ}C$, r = 30% and V = 8 m/s. Evidently, the experimental

result is in good agreement with the evaporation rate calculated by the formula and the one extracted from the nomograph.

Table 2.2 - Comparison of evaporation rates measured during the experiments performed in this research on conventional concrete with 0.38 w/c ratio, with the evaporation rates calculated by Uno's formulas and ACI nomograph.

Method	Uno's formula	ACI nomograph	Experiment
Evaporation rate ($kg/m^2/h$)	1.09	1	1.13

However, even if the water evaporation rate is accurately determined based on the above methods, still there is no guarantee that it can be applicable and reliable indicator of the cracking onset. That is due to the fact that, as mentioned earlier, the evaporation rate has to exceed the concrete bleed rate in order to cause plastic shrinkage (Powers 1969).

Besides, these formulas and nomograph seem to be only practical for predicting the evaporation rate of free water and not a water layer over concrete surface. According to the experimental results of this particular project at LTU, evaporation rate of a free water surface is almost constant, while the rate by which bleed water evaporates from a concrete surface decreases gradually, due to the reduction in the amount of the water being drained to the surface,see Figure 2.7. Menzel and Uno's formulas and the ACI nomograph, thus, give an overestimated value for evaporation. They should be further developed by including the time effect in the evaporation prediction process.

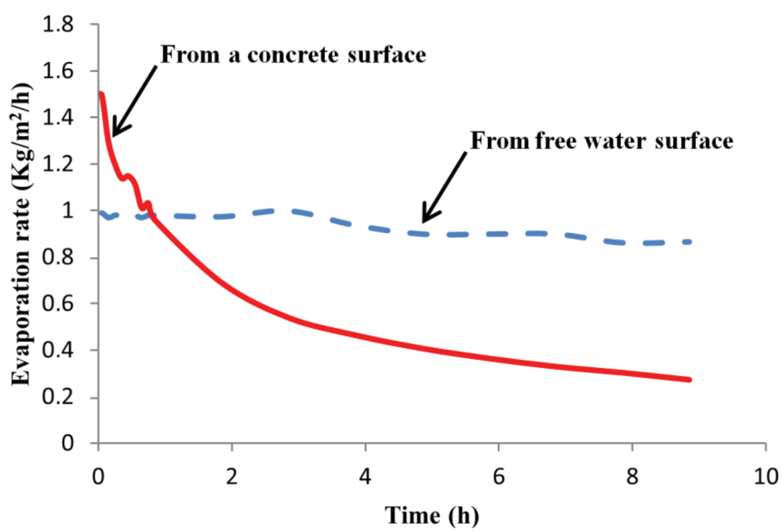

Figure 2.7 - Evaporation rate of free water and water accumulated on surface of conventional concrete with 0.38 w/c ratio. The figure plots results of experiments performed in this particular PhD project.

2.4 Capillary pressure

Due to the irregularity of particle arrangement in the concrete paste, the air-entry (Figure 2.8, Level D) does not occur simultaneously in all pores (Slowik & Schmidt 2010) (see also Figure 2.4). In other words, air-entry is rather a local event than a universal one. Therefore, different values for maximum capillary pressure may be measured in different locations of the concrete specimen.

Slowik and Schmidt (2008) performed experiments on cement paste samples, using two pressure sensors in different locations. Each sensor measured different maximum capillary pressure,Figure 2.9. The same phenomenon was observed during experiments carried out in this study (see Papers III and IV). Hence, the maximum capillary pressure at a certain location does not represent the absolute maximum capillary pressure in the concrete. In addition, the capillary pressure may break down if the sensor tip penetrates an air bubble inside the concrete (Slowik & Schmidt 2010).

However, at a given depth, the rate of capillary pressure development (i.e. slope of the ascending part of capillary pressure-time curve) is identical, regardless the location of the sensors (see Figures 2.9 and 2.10). This means that, the amount of the capillary pressure in the pore system is almost the same everywhere, especially in the first few hours after casting and before the air-entry point.

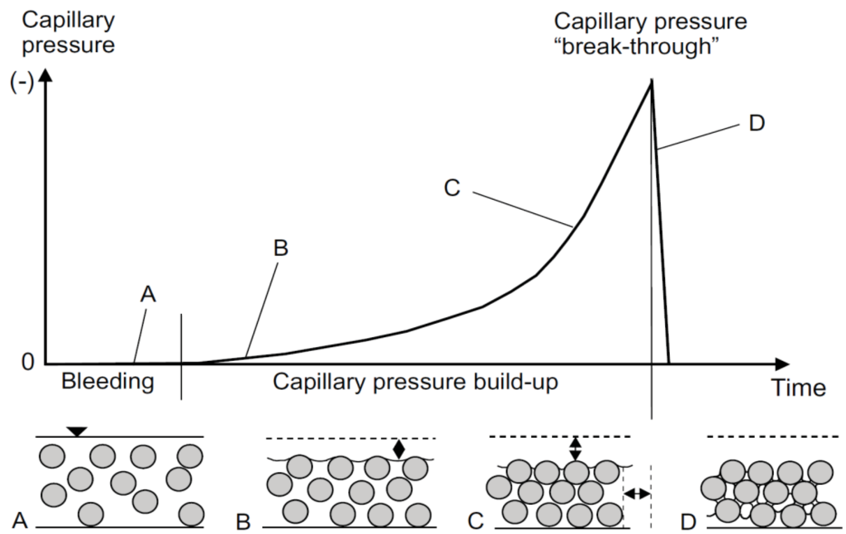

Figure 2.8 - Mechanism of capillary pressure build-up. (see also Figure 2.4), from Slowik, et al. (2008).

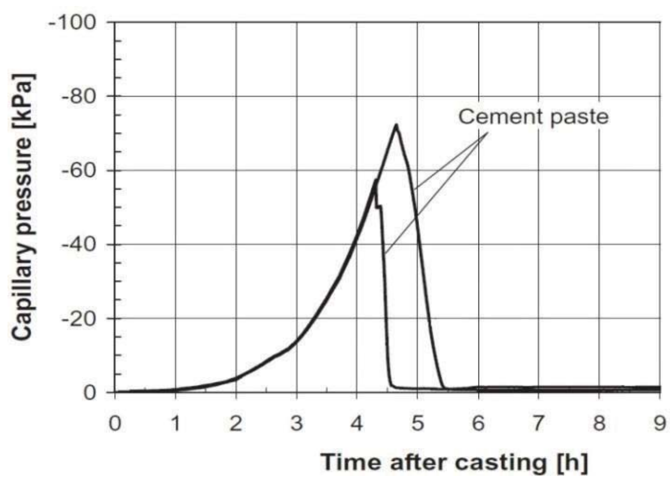

Figure 2.9 - Difference in maximum absolute capillary pressure in different locations, measured at a depth of 4 cm of 6 cm height of cement paste specimen, based on Slowik, et al. (2008).

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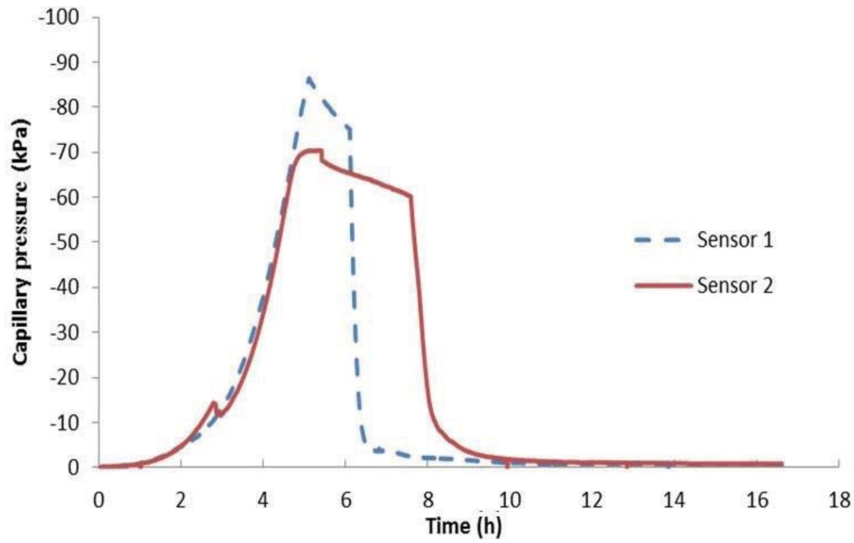

Figure 2.10 - Identical capillary pressure build-up rates in different locations of the same concrete sample, from Paper III.

According to Gauss-Laplace relation (Eq.2.4), capillary pressure in the pore system is inversely proportional to the radius of curvature of the meniscus (see Figure 2.11) (Sayahi, et al. 2014):

$$P_c = -\frac{2\gamma_w}{R} \cdot \cos\theta = -\frac{2\gamma_w}{R'} \qquad (2.4)$$

where
P_c = capillary pressure in the pore liquid (Pa)
R = radius of curvature of the meniscus in case of full wetting (θ = 0)
R'= radius of curvature of the meniscus for an arbitrary wetting angle (θ > 0)
γ_w = surface tension of the pore liquid (0.073 N/m for water)
θ = wetting angle, (deg.).

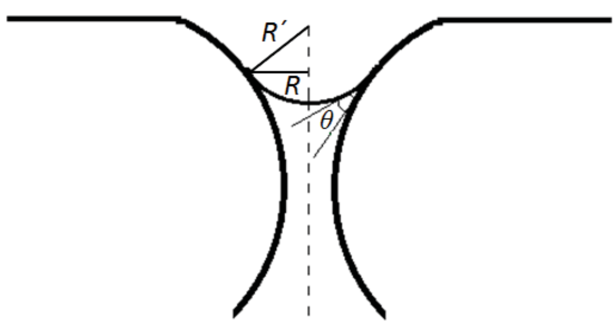

Figure 2.11 - Schematic representation of a water meniscus in an axisymmetric pore perpendicular to the surface of a solid porous material, from Paper III.

On the other hand, Kelvin's equation, relates the capillary pore pressure to the relative humidity (RH):

$$Ln(RH) = -\frac{2 \cdot \gamma_w \cdot M_w}{\rho_w \cdot R \cdot T \cdot R'} = \frac{P_c \cdot M_w}{\rho_w \cdot R \cdot T} \quad (2.5)$$

where
RH = ambient relative humidity just above the pore,
γ_w = surface tension of the pore liquid (0.073 J/m^2 for water)
M_w = molar mass of water (~0.018 kg/mol)
ρ_w = density of water, (kg/m^3)
R = ideal gas constant, (8.314 J/mol K)
T = absolute temperature in Kelvin, (20 ˚C ≈ 293 K)
R' = radius of curvature of the meniscus for an arbitrary wetting angle (θ > 0)
P_c = capillary tensile pressure, (Pa)

Eq.2.5 gives the maximum RH that allows the pore liquid (in this case water) to evaporate. Accordingly, capillary pore pressure can be obtained by combining Eq.2.4 and 2.5:

$$P_c = \frac{\rho_w \cdot R \cdot T}{M_w} \cdot \ln(RH) \quad (2.6)$$

where
P_c = capillary tensile pressure, (Pa)
ρ_w = density of water, (kg/m^3)
R = ideal gas constant, (8.314 J/mol K)
T = absolute temperature in Kelvin, (20 ˚C ≈ 293 K)
M_w = molar mass of water (~0.018 kg/mol)
RH = ambient relative humidity, (%).
As might be seen, capillary pressure is strongly dependent on the relative humidity, due to its logarithmic expression. Hence, even small reduction of RH significantly increases the capillary pressure,see Figure 2.12.

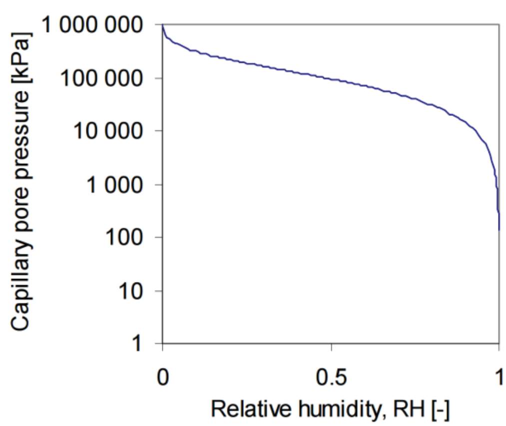

Figure 2.12 - Relation between relative humidity and capillary pressure at 20°C. The pressure is negative and logarithmic, from Esping (2007).

Based on Carman (1941), a relation was proposed by Powers (1996) for determining maximum capillary pressure in concrete, which was modified by Cohen (1990):

$$P = 1\times 10^{-3}\,\frac{\gamma \cdot S}{w/c} \qquad (2.7)$$

where
P= capillary tensile pressure, (MPa)
γ = surface tension of the pore liquid (0.073 N/m for water)
S = mass specific surface area of cement, (m^2/kg)
w/c = water/cement ratio by mass, (-)
The constant 10^{-3} has the dimension mass density (kg/m^3).

It can be seen in Eq.2.7, that the maximum capillary pressure (P) is directly proportional to γ and *S*, and inversely proportional to w/c ratio. It means that keeping other variables constant, concrete with higher w/c ratio and lower γ and *S* is less suspected to experience plastic shrinkage cracking, if the maximum pressure is considered as the main influencing parameter (Dao, et al. 2010). This needs to be further investigated, since according to some Swedish tests (Sayahi, et al. 2016, Löfgren, et al. 2006) SCC with high w/c ratio is significantly prone to plastic shrinkage cracking.

Moreover, assuming constant γ and w/c ratio in Eq.2.7, capillary pressure (P) is directly proportional to mass specific surface area of cement (*S*). In other word, maintaining all conditions similar, any difference in plastic shrinkage characteristics (i.e. strain and cracking) would be due to the difference in surface area or particle size of the solid material ((Cohen, et al. 1990). This was also observed by Pihlajavaara (1974) who suggested that the maximum capillary pressure in concrete with spherical non-porous solid aggregates can be determined as:

$$P = 2.6\times 10^{-7} \cdot \gamma \cdot S \cdot \rho \qquad (2.8)$$

where
P = capillary tensile pressure, (MPa)
γ = surface tension of the pore liquid (0.073 N/m for water)
S = mass specific surface area of cement, (m^2/kg)
ρ = solid density of cement, (kg/m^3)

Comparison between the experimental results of this project and the outcomes of Eq.2.7 and 2.8 shows that while the former seems to overestimate the maximum capillary pressure; the latter can fairly predict the real pressure value. Assuming γ = 0.073 N/m, S = 2000 m^2/kg, ρ = 3080 and w/c = 0.67 the maximum capillary pressure based on Eq. 2.7 and 2.8 are 0.218 MPa and 0.117 MPa, respectively. The maximum pressure value in the tests performed in this work, with the mentioned assumptions, is 0.088 MPa which is far from the outcome of Eq.2.7, but in fair agreement with the pressure value calculated based on Eq.2.8.

Cohen and Pihlajavaara´s equations can, thus, interpret the influence of fine material on the plastic shrinkage cracking tendency of the concrete. Experiments ((Löfgren, et al. 2006, Sayahi, et al. 2016) have shown that the risk of plastic shrinkage cracking increases with increasing the amount of the fine materials in the concrete mixture. The finer the binder is, the narrower the pores would be in the concrete pore system, which according to Eq.2.4 will increase the negative capillary pressure in the pore liquid.

As already indicated, it should be noted that Eqs.2.5 to 2.8 only calculate the maximum capillary pressure in the pore system. It is not possible to determine the pressure in different ages after casting and therefore the rate of capillary pressure development cannot be specified. The only equation that may offer this possibility is Eq.2.4. However, it is really complicated, if not impossible, to measure the radius of the water meniscus versus time after placement. Hence, the capillary pressure *build-up* rate cannot be determined theoretically based on the current knowledge.

2.5 Main factors affecting plastic shrinkage cracking

Figure 2.13 summarizes the process of plastic shrinkage cracking and the factors which can affect the phenomenon. A deep comprehension on how these factors influence the whole cracking process can lead to invention of new crack preventative methods. Some of the factors are briefly described in the following.

2.5.1 Water/cement ratio

Water/cement ratio significantly affects the plastic shrinkage cracking tendency. Assuming constant mixture constituents, higher w/c ratio causes more bleeding water and vice versa. In case of high w/c ratio, thus, it takes longer time for the surface water layer to disappear due to evaporation and consequently delays the capillary pressure build-up in the pore system.

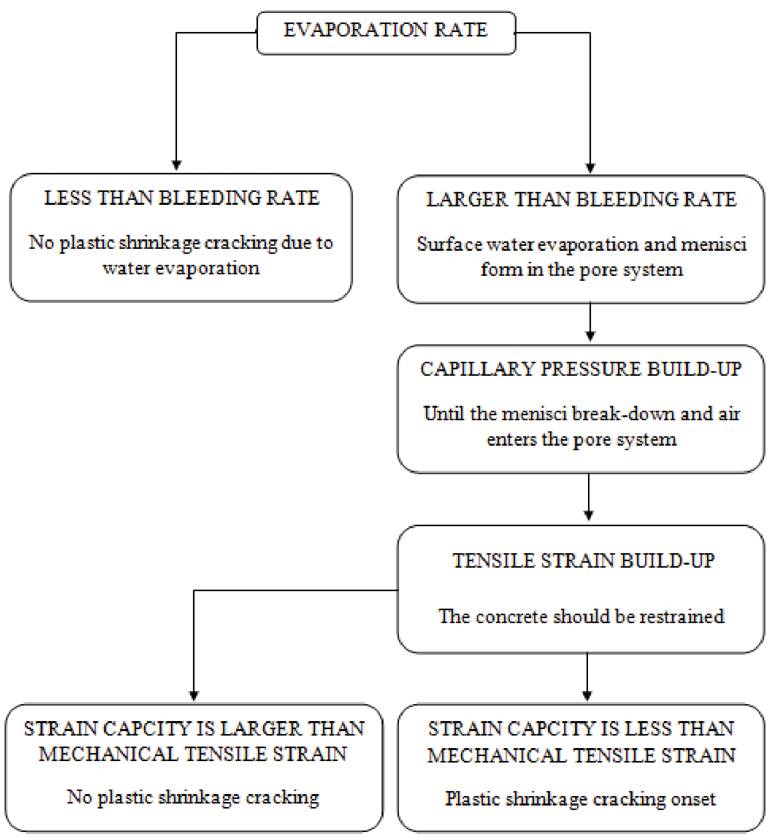

Figure 2.13 – Plastic shrinkage cracking flowchart, based on Paper II.

However, this is highly dependent on the concrete mix. A lower amount of cement in SCC with low w/c ratio often is compensated with more fines (e.g. filler) in order to avoid segregation and reduction of durability and serviceability. This leads to formation of finer pore system inside the concrete with shorter inter-particle distances. According to Eq.2.4, capillary pressure is higher in narrower pores, which means that the solid particles on the pore's perimeter wall experience higher tensile stresses and consequently, the total plastic shrinkage of the concrete member increases.

Moreover, it is known that a lower w/c ratio causes less bleeding (in conventional concrete) and thus increases the risk of cracking (Lund, et al. 1997). On the other hand w/c ratio has an inverse relation with the concrete strength. Research (Samman, et al. 1996) has shown that high-strength concrete mixtures (containing more cement) have low bleeding rate and subsequently higher risk of plastic shrinkage cracking. An optimized w/c ratio can, thus, reduce the risk of plastic shrinkage cracking, while the strength of the concrete is not diminished so much. Löfgren and Esping (2006) concluded that if the w/c ratio is in region of 0.55, the cracking tendency of the concrete decreases significantly. This optimum region of w/c ratio, in this particular work, is determined to be between 0.45 and 0.55 (see Section 4.4). Löfgren and Esping (2006) also observed that concretes with w/c ratio lower than 0.55 are more prone to autougenous shrinkage cracking, while those with w/c ratio higher than 0.55 predominantly crack due to evaporation (see Figure 2.14).

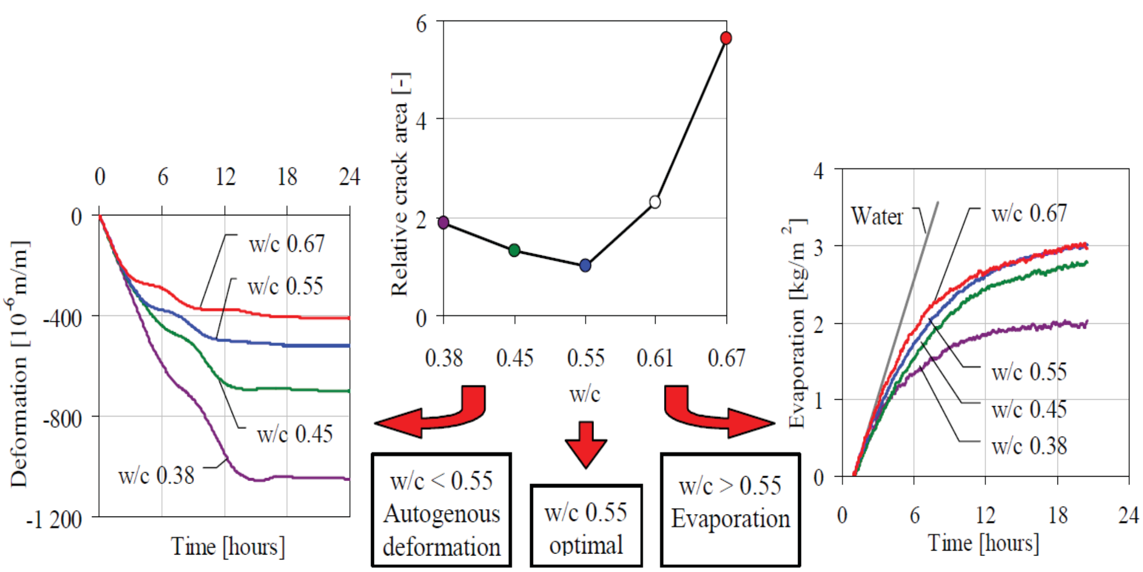

Figure 2.14 - Separation of autougenous and evaporation induced shrinkage. w/c ratio less than 0.55 causes autogenous shrinkage cracking, while w/c ratio more than 0.55 increases the risk of plastic shrinkage cracking. from Esping & Löfgren (2005).

2.5.2 Additives

Several studies have been carried out to find new admixtures in order to reduce the plastic shrinkage of concrete. These admixtures show high practicality in reducing evaporation rate, settlement, negative capillary pressure and plastic shrinkage formation. For instance, it has been concluded that cellulose-based viscosity modifying agent (stabilizer) causes reduction of the evaporation rate in cementitious material (Lin & Huang 2010).

Aaccelerators (ACC) and retarders have a strong influence on the plastic shrinkage cracking tendency. Some experiments (Kronlöf, et al. 1995, Combrinck & Boshoff 2013) showed that accelerator admixtures cause higher plastic shrinkage and total crack area, while retarders act contrary. However, other experiments (Soroka 2003, Esping & Löfgren 2005) showed that excessive usage of retarder admixtures may increase the risk of plastic shrinkage cracking due to the slower strength gain of the concrete.

On the other hand, superplasticizer (SP) reduces the need for water in the concrete mixtures i.e. less bleed water. This reduction of surface water may however not increase the risk of cracking, as the SP modifies the surface tension and prevents or delays the onset of plastic shrinkage crack formation (Cabrera, et al. 1992). Nevertheless, SP acts as a retarder and delays the hydration which means longer dormant period and slower strength gaining rate. Experiments on SCC have shown that a higher SP dosage increases the cracking tendency of the fresh concrete (Esping & Löfgren 2005).

Furthermore, experiments proved that a shrinkage-reducing admixture (SRA) reduces the plastic shrinkage cracking tendency by decreasing the evaporation, settlement and the surface tension (Lura, et al. 2007).

2.5.3 Fibres

Fibres (steel and/or polypropylene) often have been used in concrete mixtures in order to reduce the width of the plastic shrinkage cracks, through stitching the concrete surface particles together. Experiments performed by Sivakumar and Santhanam (2006) show that a combination of steel and polypropylene fibres (hybrid fibres), can reduce the width of the plastic shrinkage cracks up to 55%. However, despite of the lower crack width, parallel cracks may form around the main crack. This phenomenon can be due to the transfer of the shrinkage stresses, through the fibres, to the surrounding areas.

2.5.4 Fines content

Fines such as fly ash, silica fume, slag, etc. lead to a larger total specific surface area of the binder, and narrower pores. Consequently, the water that is supposed to be transported to the concrete surface will be trapped inside and adsorbed by the fine particles, resulting in lower bleeding rate compared to a concrete with lower volume of fines. Cohen et al. (1990) concluded that higher surface area of the particles leads to higher tensile capillary pressure and eventually higher probability of plastic shrinkage crack formation. Moreover, experiments performed by Esping and Löfgren (2005) showed that silica fume increases the crack tendency in the concrete, despite of the evaporation reduction. Accordingly, using high proportion of fine material in the concrete mixture is not favourable as regards to plastic shrinkage cracking.

2.5.5 Depth of the concrete section

A deeper concrete member typically experiences more settlement. As a result, more water is being transported to the concrete surface trough the pore system leading to a larger water accumulation on the surface. This means that the surface water layer evaporation takes longer time, causing delay in capillary pressure build-up. Consequently, a deeper concrete section is less prone to plastic shrinkage cracking (Van Dijk & Boardman 1971, Schiessl & Schmidt

1990). However, due to the high degree of settlement, the concrete may instead be vulnerable to settlement cracking, typically formed above the reinforcement bars, which may facilitate the ingress of chlorides and other harmful substances.

2.5.6 Curing measures

Plastic shrinkage cracks can be avoided through several post-casting curing measures. These measures in general aim at reduction of the surface water evaporation. For instance, sealing the concrete surface (e.g. covering the concrete with plastic sheet) decreases the evaporation rate and consequently can lead to a crack-free concrete. In another case, experiments have shown that evaporation of the surface water can be suppressed through spraying aliphatic alcohols over the fresh concrete surface (Cordon & Thorpe 1965, Hedin 1985).

Compensating the evaporated water (rewetting) is another way to protect the fresh concrete against plastic shrinkage cracking. Fogging the concrete surface, on one hand, reduces the evaporation rate through increasing the ambient relative humidity, and on the other hand, replaces some lost surface water due to evaporation (Slowik & Schmidt 2010). In addition, using a wind breaker to prevent or reduce the air flow over the concrete surface can be another efficient way to reduce the evaporation (Uno 1998).

2.6 Concluding remarks

Based on what has been mentioned so far, the following remarks can be made:

- Although, concrete in the plastic stage is still fluid and workable, after a while it will have enough rigidity, so an initial form of Hooke's stress-strength law can be applicable. Hence, the ultimate goal in preventing plastic shrinkage cracking is to keep the induced tensile stresses below the very low tensile strength of the concrete.
- The main driving force behind plastic shrinkage cracking is not the evaporation alone, but also the way that evaporation affects the development of capillary pressure development in the pore system, while the concrete is still plastic.
- Commonly used evaporation rate prediction techniques may not be applicable for determining the probable rate of evaporation from a concrete surface, since the time effect is not considered.
- The main parameter affecting the capillary pressure development is the radius of the capillary pore, which is a function of the concrete mix design.
- The rate of capillary pressure development cannot be determined theoretically based on the current knowledge.
- A higher w/c ratio increases the risk of plastic shrinkage cracking. On the other hand, reducing the w/c ratio converts to crack inducing mechanism to autogenous shrinkage.
- Plastic shrinkage cracking can be encountered by several pre- and post-casting measures. While post-casting measures are focused on compensating the evaporated water and/or reducing it, pre-casting measures should aim at avoiding and/or controlling the parameters that may influence the shrinkage of the concrete e.g. SP, fines, etc.

3. TEST METHODS AND MEASURING TECHNIQUES

3.1 General

As mentioned, plastic shrinkage of the fresh concrete is the physical component of the early-age shrinkage, which depends on several geometrical and environmental conditions. During the plastic stage, concrete deforms both vertically (i.e. settlement) and horizontally. By measuring these two deformations, the volumetric shrinkage can be calculated. Displacement transducers (e.g. LVDT, laser displacement sensor, strain gauge, etc.) are thus, often utilized. Since concrete elements with high surface to volume ratio are of high interest, specimens in form of small slabs are mainly used in experiments. The concrete surface should be exposed to the surrounding in order to facilitate the evaporation. The test should take place in controlled and constant ambient conditions (i.e. RH, temperature, wind velocity). It is, thus, recommended to perform the experiments in a climate chamber.

As the amount of the evaporated water is considered equal to sample's weight loss, the specimen can be placed on load-cells in order to achieve a continues measurement. The capillary pressure is another parameter that should be measured, using sophisticated pressure sensors. These sensors are filled with degased water and can be installed either vertically and/or horizontally. Furthermore, the internal temperature can be measured by thermo threads or any other type of standard temperature sensors. The experiments last for few hours after casting but no more than 24 hours. All the measurements are to be started shortly after the concrete placement and stopped prior to the demoulding.

In the following, experimental method and the measuring techniques used in Papers III and IV are briefly described. More information can be found in the appendices.

3.2 Test methods

3.2.1 Rectangular mould test setup

For part of the experiments performed in this work, a rectangular mould (1200x400x90 mm) has been designed based on the experimental setups used by Hedin (1985) and Lund et al. (1997), Figure 3.1. The frame is made of UPE80-beams placed on a 1 mm thick stainless steel baseplate. The gaps between the mould and the baseplate are sealed by Latex. Three rebars (8 mm in diameter) are installed on each side of the mould to restrain the concrete element. The rebars are fixed against 18 rods in total around the mould (6 rods along the long- and 3 rods along the short-side). Each rod penetrates the concrete by 60 mm.

A 50 cm wide fan is used to produce wind with constant velocity on the slab surface, varying from 0 to 7 m/s in different trials. To ensure fairly constant and laminar wind velocity, a wind tunnel is placed on the slab to conduct the wind over the surface. The wind tunnel is manufactured with Plexiglas to facilitate the visual inspection of the concrete surface.

The mould is placed on four load-cells and the weight loss (i.e. the evaporation), is documented per second. Besides, the internal temperature and capillary pressure are measured by thermo threads and CPSS sensors (see Section3.2.4) respectively. The experiment continues for 24 hours after casting. Then, the cracking tendency is calculated based on the crack area, which is defined as the crack length multiplied by the crack width. This test setup in this particular work was used only for studying conventional concretes.

Figure 3.1 – Two rectangular mould test setups with fans and Plexiglas wind tunnels, placed on four load-cells.

3.2.2 ASTM C 1579

ASTM C 1579, Figure 3.2, is a test method developed mainly in order to compare the plastic shrinkage cracking behaviour of different concrete mixtures containing fibre reinforcement under prescribed conditions of restraint and moisture loss that are severe enough to produce cracking before final setting of the concrete (ASTM 2006). However, its application is not limited to only fibre reinforced concrete and can be used in studying other parameters as well.

The big metal notch insert in the middle, is the stress riser which acts as a crack initiation point. The other two smaller metal inserts on the sides serve as internal restraints. The surface of the metal inserts and the mould sides was coated with a thin layer of oil, in order to reduce bond between the concrete and mould. The mould should be placed in a climate chamber in order to control the ambient conditions. Since many other variables such as cement fineness, aggregate gradation, aggregate volume, mixing procedures, slump, air content, concrete temperature and surface finish can also influence potential cracking, attention shall be paid to keep these as consistent as possible from mixture to mixture (ASTM 2006).

In the experiments performed in this particular project, water evaporation, capillary pressure, internal temperature, settlement and horizontal deformation in addition to the atmospheric variables were continually measured during the test. The test continues until the time of final setting is reached. At 24 hours after mixing the average crack width is determined. Moreover, ASTM suggests a Cracking Reduction Ratio (CRR), which defines the percentage of reduction in the crack width in the Fibre-Reinforced Concrete (FRC), as:

$$CRR = \left[1 - \frac{Average \quad crack \quad width \quad of \quad FRC}{Average \quad crack \quad width \quad of \quad control \quad concrete \quad mixture}\right] \times 100\% \qquad (3.1)$$

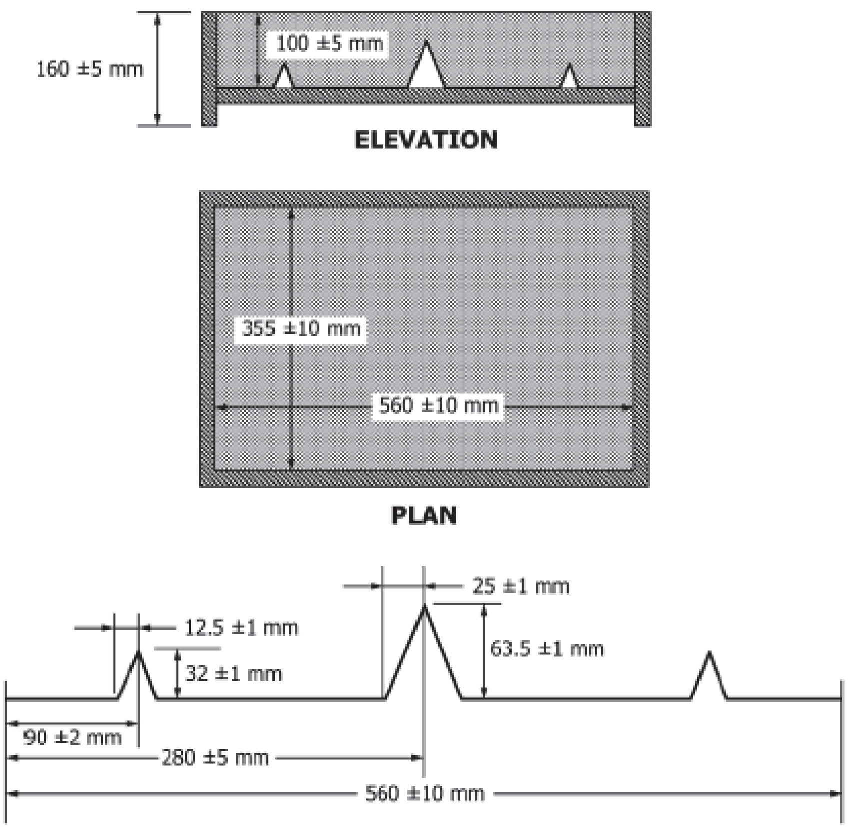

Figure 3.2 - Geometry of the ASTM C 1579 mould, from ASTM (2006).

However, it seems that the concrete specimen in ASTM C 1579 is not restrained enough to hinder the shrinkage and crack. During the experiments at LTU, the concrete cracked very seldom, despite of the significant horizontal deformation. This problem also was observed by other researchers such as Boshoff (2013) and Sivakumar (2006), where they had to modify the mould in order to increase the lateral restraint. More information regarding ASTM C 1579 test method are given in Appendix A.

3.2.3 Ring test method (NT BUILD 433)

The results presented in Papers III and IV are based on experiments performed using a ring test method (NORDTEST-method NT BUILD 433). It was first developed by Johansen and Dahl at NTNU (1993). The method is intended to determine the influence of mixture constituents on the cracking potential of fresh concrete at a “macro” level. Esping and Löfgren (Esping & Löfgren 2005) used a modified ring test method in their experiments which had different sample thickness, environmental conditions and cracking tendency evaluating method. The utilized ring test method in this study is deviated from Esping and Löfgren’s method by the ambient temperature and the capillary pressure measurement technique (see next section).

In this method, the mould consists of two concentric steel rings which are fixed to a stiff stainless steel baseplate. The surface of the baseplate is smooth and coated with a thin layer of oil. A set of three identical moulds is used. The depth of each mould is 80 mm and the diameters of the inner and outer rings are 300 and 600 mm respectively. To provide crack initiation points, steel ribs (stress raisers) are attached to the rings (see Figures 3.3 and 3.4). More information are presented in Appendix B.

After placing the concrete between the two rings, the mould is covered with a transparent air funnel attached to a suction fan, giving 4.5 m/s wind velocity across the concrete surface. During this particular investigation, the ambient temperature and relative humidity were 20±1˚C and 35±3% respectively. The weight loss (i.e. the evaporation), capillary pressure and internal temperature are recorded continually.

One of the three specimens is placed on three load-cells (scales) in order to record the evaporation per second. During these experiments, the capillary pressure is measured in 15 s intervals by means of two wireless capillary pressure sensors filled with degassed water (see Section3.2.4), which were inserted vertically down to 4 cm distance from the concrete surface right after casting. The internal temperature is recorded in 1 s intervals with a thermo thread located at 2 cm distance from the bottom of the mould. All the measurements start 60 minutes after the concrete placement and are finished 18 hours later.

The concrete surface in all three specimens is visually inspected every 30 minutes in order to determine the time of the probable crack initiation. At the end of the experiment, the crack width and the crack length were measured by a digital microscope (to an accuracy of 0.05 mm) and a digital measuring wheel (to an accuracy of ±1 mm) respectively. The average crack area of the three moulds is then calculated, as suggested by Esping and Löfgren (2005), as:

$$Average \quad crack \quad area = \frac{\sum (crack \quad length \times crack \quad width)}{3} \tag{3.2}$$

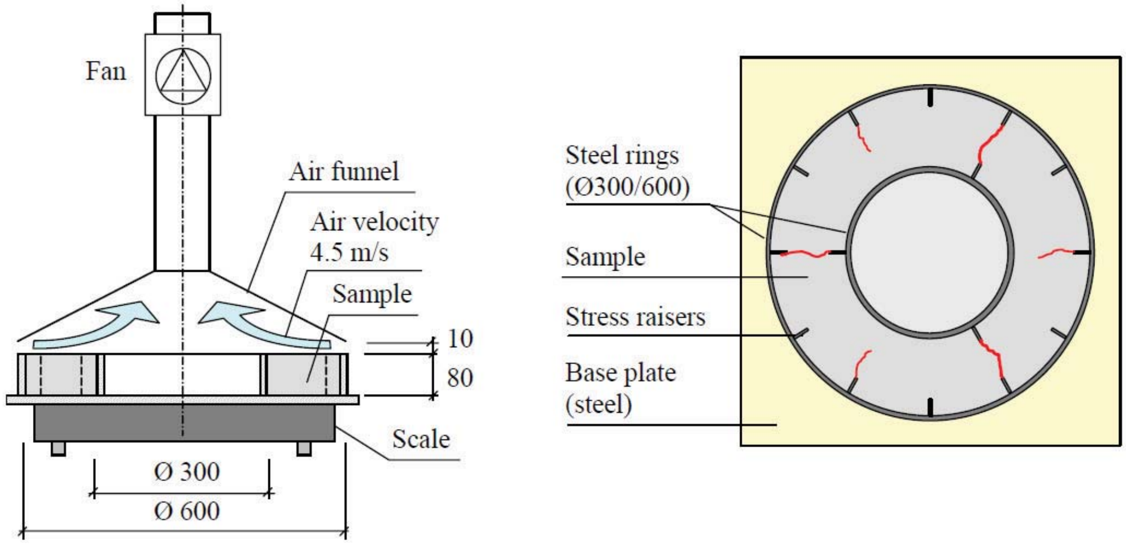

Figure 3.3 - Ring test method setup for plastic shrinkage cracking tendency determination, based on Löfgren, et al. (2006) (dimensions in mm).

Figure 3.4 - Arrangement of the three moulds in the ring test method.

3.2.4 Capillary pressure

During the experiments reported in Papers III and IV, the capillary pressure was measured with Capillary Pressure Sensor System (CPSS), manufactured by Research and Transfer Centre (FTZ) at the Leipzig University of Applied Science (HTWK Leipzig) (see Figure 3.5). The cone of the sensor is to be filled with degased water and should penetrate the concrete surface down to about 5 cm distance from the concrete surface. CPSS can measure the capillary pressure down to -100 kPa. Each sensor, in addition to the capillary pressure, measures the air temperature, the ambient RH and the brightness (i.e. solar radiation). The sensors are wirelessly connected to a base station which in turn is connected to a computer. The sending frequency is 2.4 GHz and the maximum radio transmission range is around 60 m. The measured data can be seen in real-time through an inter-active interface on a software installed on the computer.

The main deviation between the ring test setup used in this study with the one used by Esping and Löfgren (2006) is the capillary pressure measurement technique. Beside the different type of sensors (Model AB 0-15 PSIG from Data Instruments was used by Esping and Löfgren), they were installed horizontally at 2 and 6 cm from the concrete surface, whereas in this study, the sensors are applied vertically.

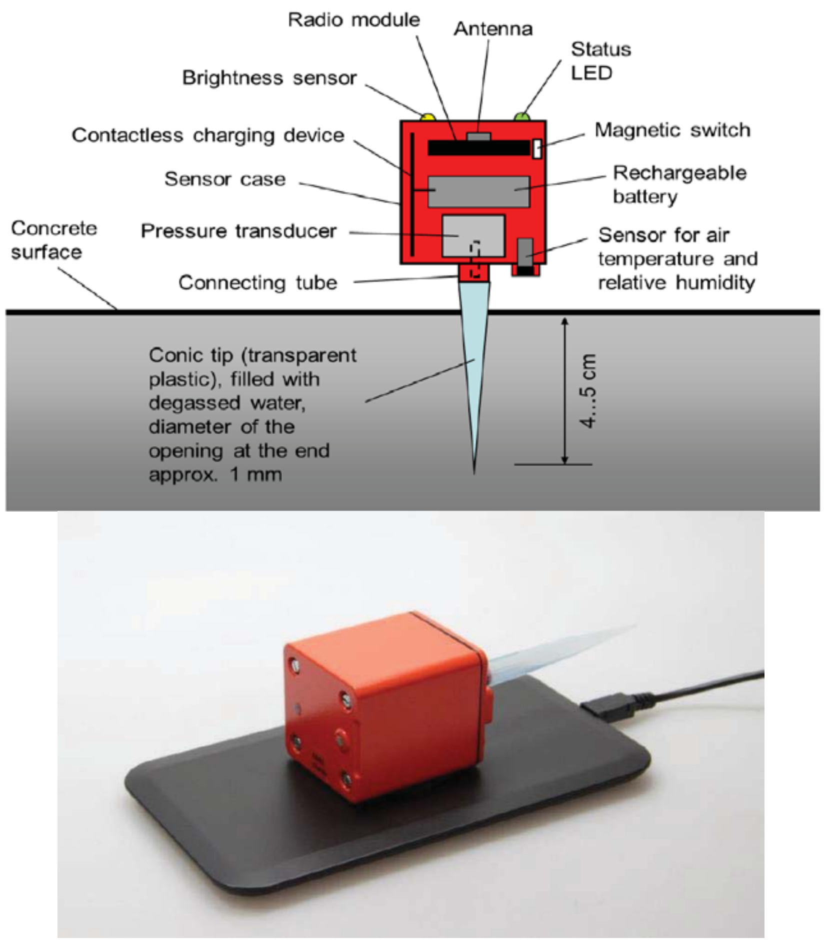

Figure 3.5 - Components of a CPSS sensor, from (CPSS user manual).

4. EXPERIMENTAL RESULTS

4.1 General

In this chapter, results of the experiments performed in this project so far, are generally presented. More details and discussions are presented in the appended papers. It ought to be mentioned that some of these results are not necessarily novel and may have been observed by other researchers as well. What is different in this work is the way that the results are analysed and utilized in order to tackle the plastic shrinkage cracking phenomenon. This will be explained more in the following.

4.2 Evaporation rate

As mentioned in Section2.3 the common evaporation prediction techniques, such as Eq. 2.1, 2.2 and ACI nomograph, are based on evaporation from a free water surface and therefore, cannot be applicable to predict the evaporation from a concrete surface. According to the findings of the performed tests (see Papers III and IV), the accumulative evaporation of free water is linear with time, while, the total evaporation from concrete surface in the specimen decreases gradually after casting (Figure 4.1). Accordingly, the evaporation rates of free water and concrete surface have completely different trend, as also shown in Figure 2.7.

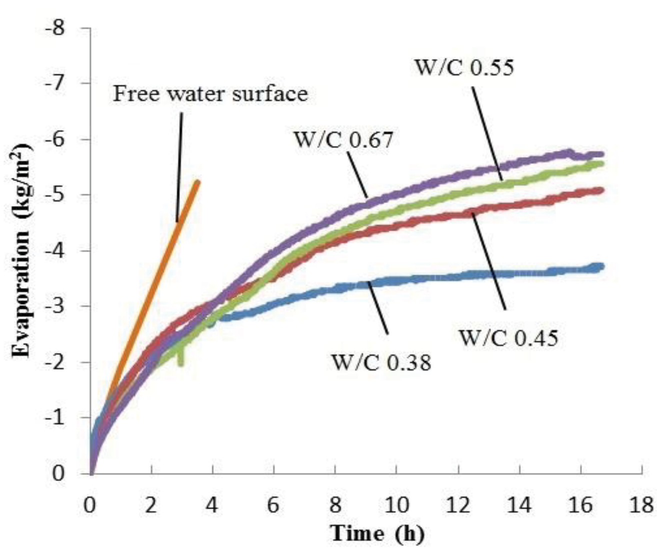

Figure 4.1 – Accumulative evaporation from a free water surface and from surface of SCCs in ring test setup with different w/c ratios i.e. 0.38, 0.45, 0.55 and 0.67, from Paper III.

4.3 Capillary pressure development rate

Capillary pressure in concrete has been known to researchers for a long time. It has been the topic of numerous studies and was discussed in many papers and books. However, it seems that, in the previous research, the role of the maximum value of the capillary pressure in plastic shrinkage cracking has been highlighted more than its rate of development.

According to the results of the experiments performed here (see Papers III and IV), despite of the local nature of the maximum capillary pressure, at any given depth, the pressure develops with the same rate, regardless of the sensor's location (see Section 2.4 and Figures 2.9 and 2.10).

Since the deformation is related to the capillary pressure is, the rate of the pressure build-up, can be an indication of the amount of the shrinkage the concrete element undergoes. For example, in Figure 4.2, the value of capillary pressure for SCC with different w/c ratios, at 4 hours after finishing the surface, can be compared. As it can be seen, the capillary pressure at this time is -38 kPa for W/C 0.67, while it is around -24 kPa for the others i.e. W/C 0.67 experiences higher shrinkage. This can also be comprehended from photos taken at the end of the experiments, where the cracks in W/C 0.67 is about 10 times wider than those in W/C 0.45 (Figure 4.3).

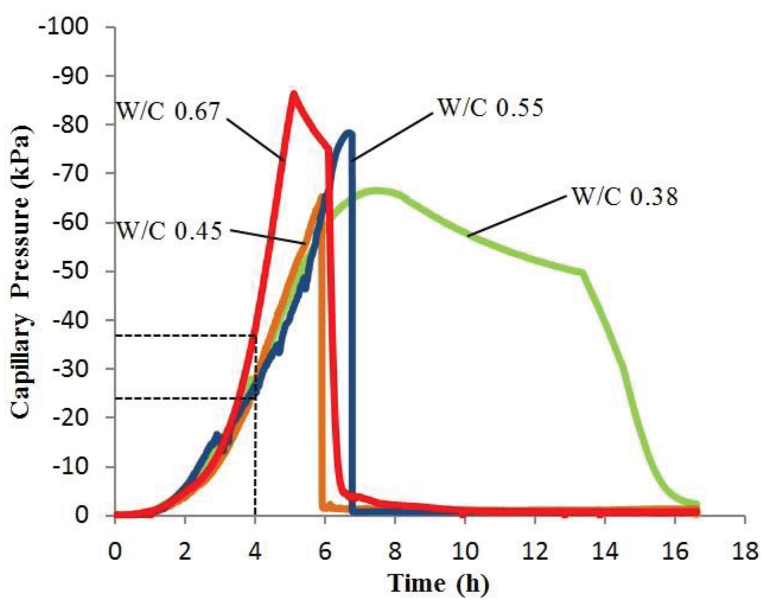

Figure 4.2 – Rete of capillary pressure build-up in SCCs with different w/c ratios i.e. 0.38, 0.45, 0.55 and 0.67, from Paper IV.

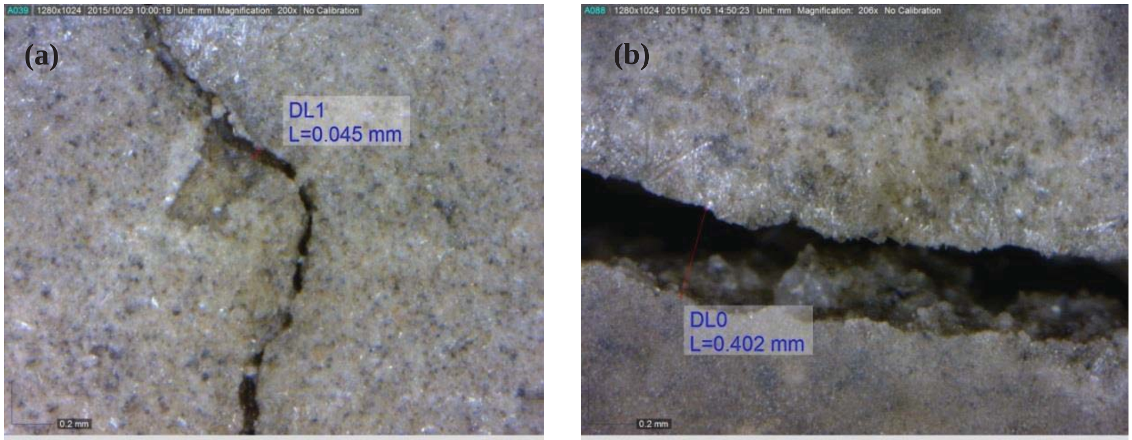

Figure 4.3 - Plastic shrinkage crack width in (a) SCC with 0.45 w/c ratio and (b) SCC with 0.67 w/c ratio at 24 hours after casting, from Paper IV.

4.4 Effect of w/c ratio on cracking

By studying the influence of w/c ratio on the cracking tendency of SCC, an optimum w/c ratio range for the lowest early-age cracking risk can be identified between 0.45 to 0.55. Any SCC with w/c ratio out of this range has a high tendency of early-age cracking, see Figure 4.4. However, it was also observed that SCC with w/c ratio less than 0.45 cracks mainly due to autogenous shrinkage, while plastic shrinkage is the main driving force behind the cracking of SCC with w/c ratio higher than 0.55 (see also Figure 2.14 and discussion in Papers III and IV). This finding is also manifested in the time of crack initiation measured during the tests (Figure 4.4), as decreasing the w/c ratio delays the cracking.

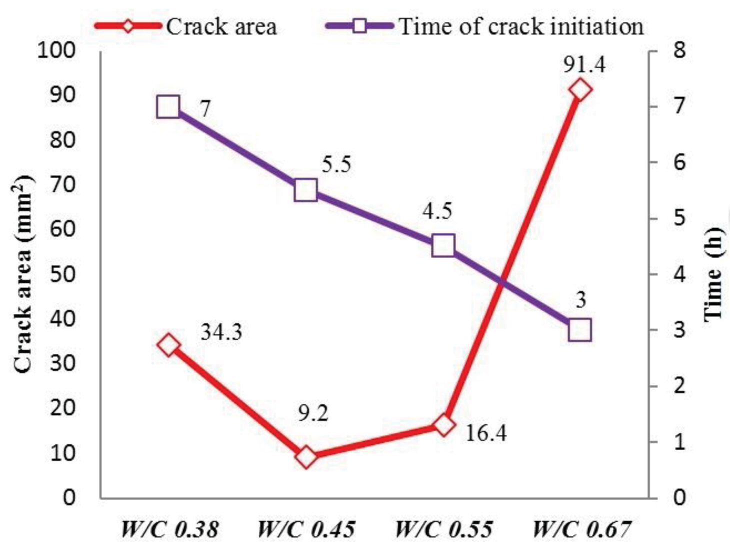

Figure 4.4 – Average crack area (calculated based on Eq.3.2) and time of crack initiation of SCCs in ring test setup with 0.38, 0.45, 0.55 and 0.67 w/c ratios, from Paper IV.

4.5 Effect of cement type on cracking

According to the tests, normal hardening Swedish Portland cements seem to increase the plastic shrinkage cracking tendency comparing to rapid hardening cements, see Figure 4.5. The reason lies in the fact that rapid hydration of the concrete leads to faster build-up of the rigid skeleton and consequently higher tensile strength.

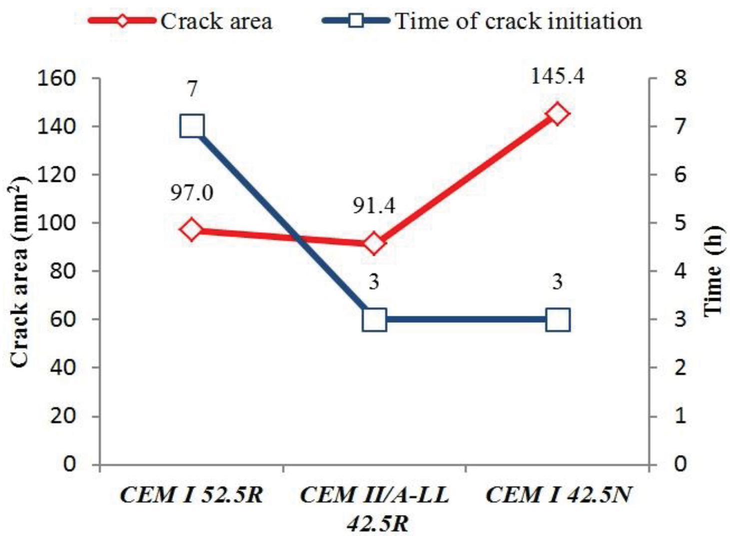

Figure 4.5 – Average crack area (calculated based on Eq.3.2) and time of crack initiation of SCCs in ring test setup produced with CEM I 52.5R, CEM II/A-LL 42.5R and CEM I 42.5N cements, from Paper IV.

4.6 Effect of coarse aggregate content on cracking

It was observed in the tests that a reduction of coarse aggregate content in the concrete mixture results in significant increase in the plastic shrinkage cracking risk, Figure 4.6. The reduced amount of coarse aggregates will be compensated by fine material, which in turn, leads to finer and narrower pores. Capillary pressure, according to Eq. 2.4, is higher in pores with smaller radius and hence, larger tensile stresses are applied on the solid particles which increase the plastic shrinkage.

4.7 Effect of superplasticizer on cracking

The retarding effect of SP increases the risk of plastic shrinkage cracking as shown in Papers III and IV, Figure 4.7. By increasing the SP dosage, the hydration rate decreases, which means that the concrete remains plastic for a longer time. This facilitates the cracking since the tensile strength gaining process is slower.

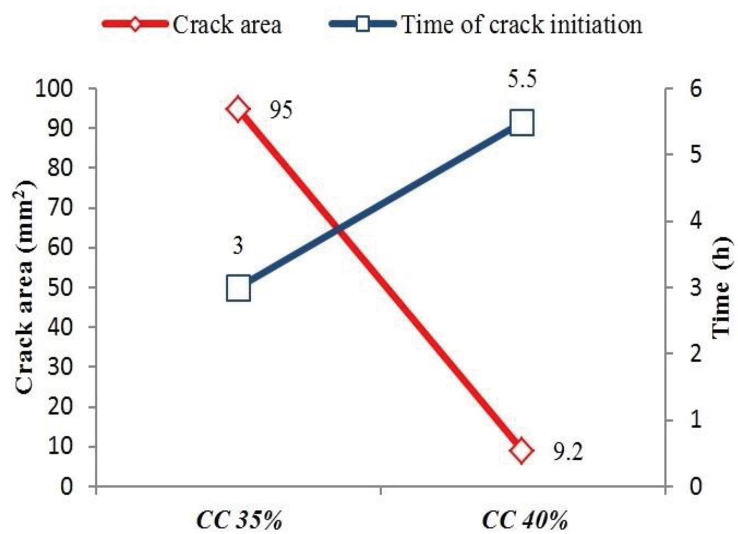

Figure 4.6 – Average crack area (calculated based on Eq.3.2) and time of crack initiation of SCCs in ring test setup with 35% and 40% of total aggregate volume coarse aggregate content, from Paper IV.

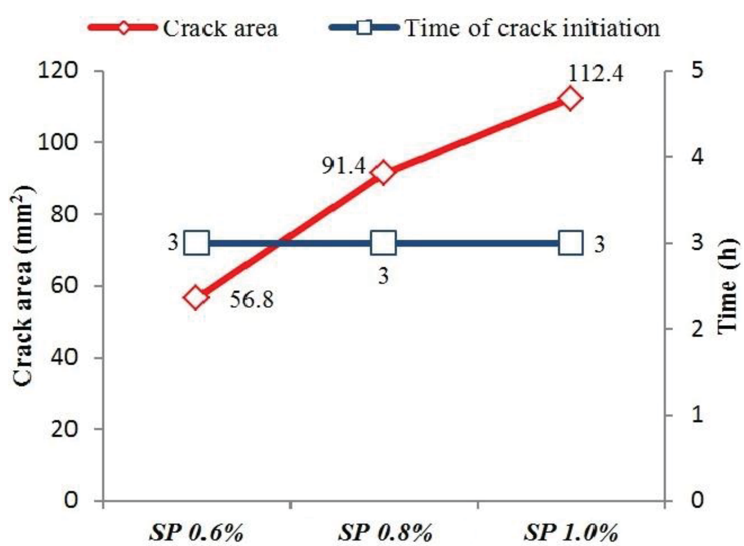

Figure 4.7 – Average crack area (calculated based on Eq.3.2) and time of crack initiation of SCCs in ring test setup with 0.6%, 0.8% and 1.0% SP dosage, from Paper IV.

5. DISCUSSION AND GENERAL CONCLUSIONS

5.1 Discussion

Early-age cracking in concrete is a result of a complex correlation of physical and chemical processes on which the cracking governing mechanisms are based. While the rapid and excessive loss of moisture, mainly due to evaporation, is the driving force behind the physically induced shrinkage (i.e. plastic shrinkage), chemical reactions between the cement constituents and water cause autougenous shrinkage. Logically different crack preventative methods should be applied based on the early-age cracks origin. Here lies the importance of separation of the governing mechanisms behind the cracking. Doing that it would be easier to find the proper crack preventative measure and the best application time (i.e. pre- and/or post-casting).

In this thesis, plastic shrinkage of concrete in general and SCC in particular has been discussed. Although autogenous shrinkage may notably influence the early-age cracking tendency of the concrete, it has been disregarded in this study and the plastic shrinkage induced cracks have been intensively investigated. Influence of several parameters (e.g. w/c ratio, additives, coarse aggregate content, ambient conditions, etc.) is studied and effort is made in order to deepen the comprehension of the crack governing mechanisms. Therefore, the probable relationship between water evaporation, capillary pressure and hydration rate is investigated.

The main characteristic of SCC is its high flowability, despite of its lower water possession. The lower amount of water is compensated by water-reducing admixtures (superplasticizer), which act as retarders and may lower the hydration rate of the concrete which leads to longer dormant period. Moreover, to avoid any potential segregation, higher amount of fines are often added to the mixture. Consequently the arrangement of the solid particles differs causing finer pore structure and shorter inter-particle distances in comparison to conventional concrete. Accordingly, the capillary pressure develops faster in the pores, which means that the concrete experience higher tensile stresses at earlier stages. Longer dormant period (i.e. delayed initial set) accompanied by higher surface tension facilitates the plastic shrinkage whereupon may significantly increase the cracking tendency. Therefore, SCC is considered to be highly prone to plastic shrinkage cracking.

During this work, it has been observed from the test results, that if the w/c ratio is between 0.45 and 0.55, the plastic shrinkage cracking risk would be low. Any concrete with w/c ratio which does not fit in this range may be endangered by plastic shrinkage cracking. It also has been observed that increasing the w/c ratio changes the crack inducing mechanism from autogenous shrinkage in concretes with low w/c ratio to pure plastic shrinkage in those with high w/c ratio. Furthermore, clear impact was detected on the evaporation, capillary pressure build-up rate, hydration rate and the crack initiation time. According to the results, evaporation is not the only driving force behind the cracking. Instead a correlation between the evaporation, the capillary pressure and the hydration rate governs the cracking tendency of the fresh concrete.

Despite of the fact that the maximum value of capillary pressure i.e. break-through point, is local and differs in different locations, but it was found that rate of capillary pressure build-up (i.e. the slope of the ascending part of the capillary pressure vs. time curve) at a certain depth is almost identical, regardless of the sensors' position. This happened in every experiment without exception. Hence, the capillary pressure development rate may give us a clue about the amount of shrinkage that the concrete element undergoes. The higher the capillary pressure development rate is, the concrete shrinks more and vice versa. However, it ought to be mentioned that this is true only if the duration of the dormant period is assumed constant.

The rate of the capillary pressure development depends on the arrangement of the solid particles and the pore system structure. As mentioned, capillary pressure is inversely proportional to the radius of the pore (water menisci). Accordingly, it is possible that in wide pores, even with higher evaporation, the capillary pressure increases with lower rate (as in case of increasing SP dosage). This means that the concrete shrinks slower. However, if the hydration rate is low, which means that the initial set is delayed, the concrete will have more time to shrink without resistance. Hence, eventually the total shrinkage is higher and accordingly is the cracking tendency.

5.2 Conclusions

Plastic shrinkage cracking is a complex interaction of several variables that may change under different circumstances and conditions at the very early ages. These variables have a direct influence on the evaporation, capillary pressure build-up rate and the duration of dormant period. The explanations offered in this thesis and the appended papers for the plastic shrinkage cracking mechanism and the role of each mixture constituent in the process facilitates gaining a comprehensive and clear vision of the phenomenon. However, considerably more information is needed to gain a clear view on the influence of each constituent, which hopefully can lead to innovation of new crack preventive measures.

Based on the findings of this study, the following remarks can be listed:

- Although, concrete in the plastic stage is still fluid and workable, after a while it will have enough rigidity to apply the Hooke's stress-strength law. The ultimate goal in preventing plastic shrinkage cracking is to keep the induced tensile stresses below the tensile strength of the young concrete.
- The main driving force behind plastic shrinkage cracking is not the evaporation alone, but the way that evaporation affects the development of capillary pressure development in the pore system, while the concrete is still plastic.
- Commonly used evaporation prediction techniques are not applicable for determining the probable evaporation of the bleed water accumulating on concrete surface, since the time effect i.e. the variation by time is not considered.
- The main parameter affecting the capillary pressure development is the radius of the pore, which is a function of the concrete mix design.

- The rate of capillary pressure development cannot be theoretically determined based on the current knowledge and physical data on the concrete.
- High capillary pressure build-up rate accompanied with high or moderate evaporation and long, moderate or short dormant period is the worst combination significantly increasing the plastic shrinkage cracking risk.
- Low capillary pressure build-up rate together with low or moderate evaporation, regardless of the duration of the dormant period, is the best case scenario preventing plastic shrinkage cracking.
- Increasing the w/c ratio in SCC, converts the early age cracking from being autogenous to pure plastic shrinkage cracking.
- Protecting concretes with high w/c ratios against evaporation reduces the risk of plastic shrinkage cracking significantly.
- Cracks in SCC produced by rapid hydrating cements are mainly autogenous, while those produced by slow hydrating cements are mainly subjected to plastic shrinkage cracking.
- Reducing the amount of the coarse aggregate in SCC accelerates the crack initiation.
- SP decreases the capillary pressure build-up rate, delays the hydration and increases the evaporation. Concretes with higher SP dosage are thus, more prone to plastic shrinkage cracking, despite of the slower capillary pressure development.
- Protecting the concrete with high SP dosage against evaporation is an effective way to prevent plastic shrinkage cracking.

5.3 Future research

In general, fully understanding the governing mechanism behind the phenomenon of plastic shrinkage cracking is not an easy task. Based on the findings, the following measures are suggested for future:

- Vertical and horizontal deformation measurement should be included in the coming experiments, in order to determine the volumetric shrinkage of the concrete and its potential relationship with the evaporation and capillary pressure.
- More tests under controlled atmospheric conditions are needed in order to develop new equations which can predict the evaporation rate of water from concrete surface. In other words, the time effect should be included in predicting evaporation rate in concrete.
- By performing more tests, a database of capillary pressure measurements under various circumstances will be provided, by which the rate of the pressure development can be modelled and theoretically calculated.
- It is highly important to confirm the general conclusions of this project by performing half- and/or full-scale tests.

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Part II

APPENDIX A:

ASTM C 1579

Standard Test Method for Evaluating Plastic Shrinkage Cracking of Restrained Fibre Reinforced Concrete (Using a Steel Form Insert).

Designation: C1579 − 13

Standard Test Method for Evaluating Plastic Shrinkage Cracking of Restrained Fiber Reinforced Concrete (Using a Steel Form Insert)[1]

This standard is issued under the fixed designation C1579; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (´) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This test method compares the surface cracking of fiber reinforced concrete panels with the surface cracking of control concrete panels subjected to prescribed conditions of restraint and moisture loss that are severe enough to produce cracking before final setting of the concrete.

1.2 This test method can be used to compare the plastic shrinkage cracking behavior of different concrete mixtures containing fiber reinforcement.

1.3 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* (**Warning—**fresh hydraulic cementitious mixtures are caustic and may cause chemical burns to skin and tissue upon prolonged exposure.[2])

2. Referenced Documents

2.1 *ASTM Standards:*[3]

C125 Terminology Relating to Concrete and Concrete Aggregates

C143/C143M Test Method for Slump of Hydraulic-Cement Concrete

C192/C192M Practice for Making and Curing Concrete Test Specimens in the Laboratory

C403/C403M Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance

C670 Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials

3. Summary of Test Method

3.1 Panels of control concrete and fiber reinforced concrete are prepared in a prescribed manner and are exposed to controlled drying conditions after finishing. The drying conditions (see Note 1) are intended to be severe enough to induce plastic shrinkage cracking in test panels made of control concrete. The evaporation rate from a free water surface is monitored by pans placed next to the panels in the environmental chamber.

NOTE 1—An important parameter in this method is the rate of evaporative water loss, which is controlled by the atmospheric conditions surrounding the test specimens. Since the concrete specimens will not always have the same rate of water evaporation as the pan of water (due to evaporative and bleeding effects), the rate of evaporation of 1.0 $kg/m^2 \cdot h$ from the pan of water represents the minimum evaporation rate that must be attained for this test (**1**).[4] The moisture loss from the concrete test panels can also be monitored and reported, however, the rate of evaporation from the free surface of the water in the pan is the parameter that should be used to quantify the drying environment.

3.2 The test is terminated at the time of final setting of the concrete determined in accordance with Test Method C403/C403M. At 24 h from initial mixing, the average crack width is determined.

3.3 A cracking reduction ratio (CRR) is computed from the average crack width for the fiber-reinforced concrete panels and the average crack width for the control concrete panels.

4. Significance and Use

4.1 The test method is intended to evaluate the effects of evaporation, settlement, and early autogenous shrinkage on the plastic shrinkage cracking performance of fiber reinforced concrete up to and for some hours beyond the time of final setting (see Terminology C125).

4.2 The measured values obtained from this test may be used to compare the performance of concretes with different mixture proportions, concretes with and without fibers, concretes containing various amounts of different types of fibers,

[1] This test method is under the jurisdiction of ASTM Committee C09 on Concrete and Concrete Aggregates and is the direct responsibility of Subcommittee C09.42 on Fiber-Reinforced Concrete.

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[2] Section on Safety Precautions, Manual of Aggregate and Concrete Testing, *Annual Book of ASTM Standards*, Vol 04.02.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] The boldface numbers in parentheses refer to the list of references at the end of this standard.

***A Summary of Changes section appears at the end of this standard**

and concretes containing various amounts and types of admixtures. For meaningful comparisons, the evaporative conditions during test shall be sufficient to produce an average crack width of at least 0.5 mm in the control specimens **(2, 3)** (see Note 2). In addition, the evaporation rate from a free surface of water shall be within 6 5 % for each test.

NOTE 2—To achieve evaporation rates that result in a crack of at least 0.5 mm in the control specimens, it may be necessary to use an evaporation rate higher than that discussed in Note 1.

4.3 This method attempts to control atmospheric variables to quantify the relative performance of a given fresh concrete mixture. Since many other variables such as cement fineness, aggregate gradation, aggregate volume, mixing procedures, slump, air content, concrete temperature and surface finish can also influence potential cracking, attention shall be paid to keep these as consistent as possible from mixture to mixture.

5. Apparatus

5.1 *Molds:*

5.1.1 For maximum coarse aggregate size equal to or less than 19 mm, use a mold with a depth of 100 6 5 mm and rectangular dimensions of 355 6 10 mm by 560 6 15 mm (see Fig. 1). The mold can be fabricated from metal, plastic, or plywood.

NOTE 3—If plywood is used for molds, the plywood should have low moisture absorption. The mold should be constructed to be lightweight and stiff. The molds, when properly constructed, should last for approximately 50 uses.

5.1.2 This test method is designed for aggregate less than or equal to 19 mm. For coarse aggregate greater than 19 mm, the depth of the mold shall be at least 65 mm plus at least 2 times the maximum coarse aggregate size.

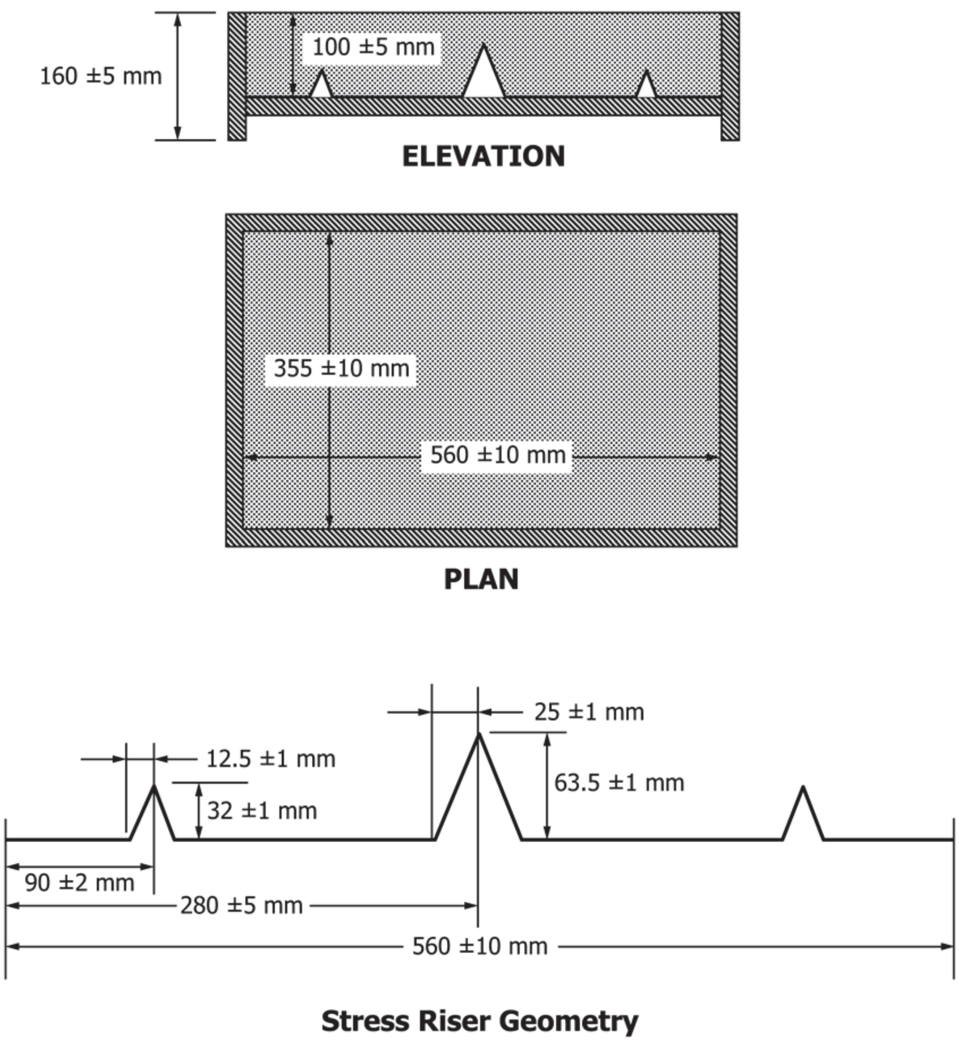

FIG. 1 Specimen and Stress Riser Geometry (4, 3)

5.2 *Stress Riser and Internal Restraints*—The internal restraints and stress riser shall be bent from one piece of sheet metal, as illustrated in Fig. 1, or made from a solid piece of steel. The sheet metal shall have a thickness of 1.2 ± 0.05 mm (18 gauge) (see Fig. 1 and Ref **2**). Two 32 ± 1 mm high restraints are placed 90 ± 2 mm inward from each end of the mold. The central stress riser is 64 ± 2 mm high and serves as an initiation point for cracking. This sheet metal stress riser with internal restraints shall fit at the bottom of the mold.

5.2.1 Use form release oil to coat the metal insert and mold sides to reduce bond with concrete. The insert and mold are considered to be properly oiled when the entire surface is coated and excess oil has been removed with a clean, dry rag.

5.3 *Variable Speed Fan(s)*—The fan(s) used shall be capable of achieving a wind speed of more than 4.7 m/s over the entire test panel surface area.

5.4 *Environmental Chamber*—The use of a fan box in an environmental chamber is a method for producing a uniform airflow over the panel surface (see Fig. 2). A clear cover over the panels will aid in obtaining uniform airflow and allow for observation of cracking. Another method of producing uniform airflow is to use a specifically designed environmental chamber as shown in Fig. 3. A commercially available heater, humidifier, and dehumidifier can be used to maintain the specified environmental condition. This test is conducted using either apparatus shown in Fig. 2 or Fig. 3 by exposing the panels to an evaporation rate of at least 1.0 kg/m^2·h (see Note 1). For the standard test, the temperature must be maintained at 36 ± 3°C, the relative humidity must be 30 ± 10 %, and the wind velocity must be sufficient to maintain the minimum evaporation rate during the test.

NOTE 4—Before casting the concrete panels, atmospheric variables in the environmental facility should be checked to determine that the necessary evaporative conditions can be achieved. A wind velocity of 4.7 m/s should be sufficient to achieve the minimum specified evaporation rate, but a higher wind velocity may be needed to obtain sufficient average crack width in some control panels.

5.5 *Sensors*—Use temperature, humidity, and wind velocity sensors to measure ambient air and concrete surface temperature to the nearest 0.5°C, relative humidity to the nearest 1 %, and air speed to the nearest 0.1 m/s.

5.6 *Vibrating Platform*—Any device that can fully consolidate the test panel that meets minimum frequency requirements as stated in Practice C192/C192M for an external vibrator is suitable.

5.7 *Surface Finishing Equipment*—An angle iron screed shall be used for the concrete after vibration. A magnesium, steel, or wood trowel shall be used for finishing the surface of the specimen after screeding.

5.8 *Monitoring Pan*—A pan suitable for exposing water to the air stream for each concrete test panel is required. The sides of the pan shall be vertical. The pan shall be of sufficient size to expose at least 0.1 ± 0.01 m^2 of water to the air stream. The exposed lip of the pan shall not extend more than 5 mm above the water level at the start of the test.

NOTE 5—The test panels and monitoring pans can be placed in an environmental chamber designed for this test method (see Fig. 3) or the pans can be placed downstream from panels in a fan box (see Fig. 2).

5.9 *Scale*—If the rate of moisture loss from test panels is required by the specifier of tests, weigh test panels with a scale having a capacity of at least 100 kg and accurate to within 0.1 % of the test load. Weigh the evaporation rate monitoring pans with a balance or scale having a capacity of at least 3 kg and accurate to within 5 g.

5.10 *Crack Measurement Tool*—Optical hand-held microscope, crack comparator, or image analysis system can be used. The measurement tool should be capable of measuring crack width to at least the nearest 0.05 mm. If an automated image analysis system is used, it should be demonstrated to provide an accurate measurement. To demonstrate the accuracy of the measurement, the system shall be used to measure a 0.5 mm notch that is machined into a piece of steel and the reported notch width shall be within ± 0.05 mm of the machined width.

6. Sampling, Test Specimens, and Test Units

6.1 *Test Panels*—Cast test panels in accordance with the applicable provisions of Practice C192/C192M, using the same source of materials, preparation, mixing and finishing procedures.

6.2 *Test Unit*—A test unit is comprised of at least two control specimens and at least two fiber reinforced concrete specimens with the same mixture proportions. A group of two control specimens has to be tested each time in order to determine the plastic shrinkage crack reduction of fiber reinforced concrete.

7. Procedure

7.1 Determine the slump of each mixture in accordance with Test Method C143/C143M.

7.2 Fabricate specimens for setting time determination in accordance with Test Method C403/C403M. If fiber reinforced concrete cannot be wet sieved readily, use the control concrete specimen to measure time of final setting of both the control and the fiber-reinforced mixtures. Place the time of setting specimens in the air stream so that they are exposed to the same environmental conditions as the plastic shrinkage panels.

7.3 Fill the panel molds using one layer. Consolidate the concrete with external vibration until the concrete is approximately level with the top of the mold. Screed each specimen perpendicular to the stress riser three times.

7.4 After screeding, trowel specimens using a predetermined number of passes. If moisture loss from the panel is to be determined, remove any waste concrete adhering to the outside of the mold and weigh each panel while in the mold.

7.5 Place a fiber reinforced concrete mixture panel and control mixture panel in the environmental chamber downstream from the fan(s) (see arrangements in Figs. 2 and 3).

7.6 Turn on the fan(s), which have been preset to achieve the air speed to obtain the required evaporative conditions (see Note 4). The evaluation of cracking commences at this time.

7.7 At the start of the test and at 30-min intervals, record air temperature, relative humidity, and air flow speed at a location 100 ± 5 mm above each panel surface. If required by the

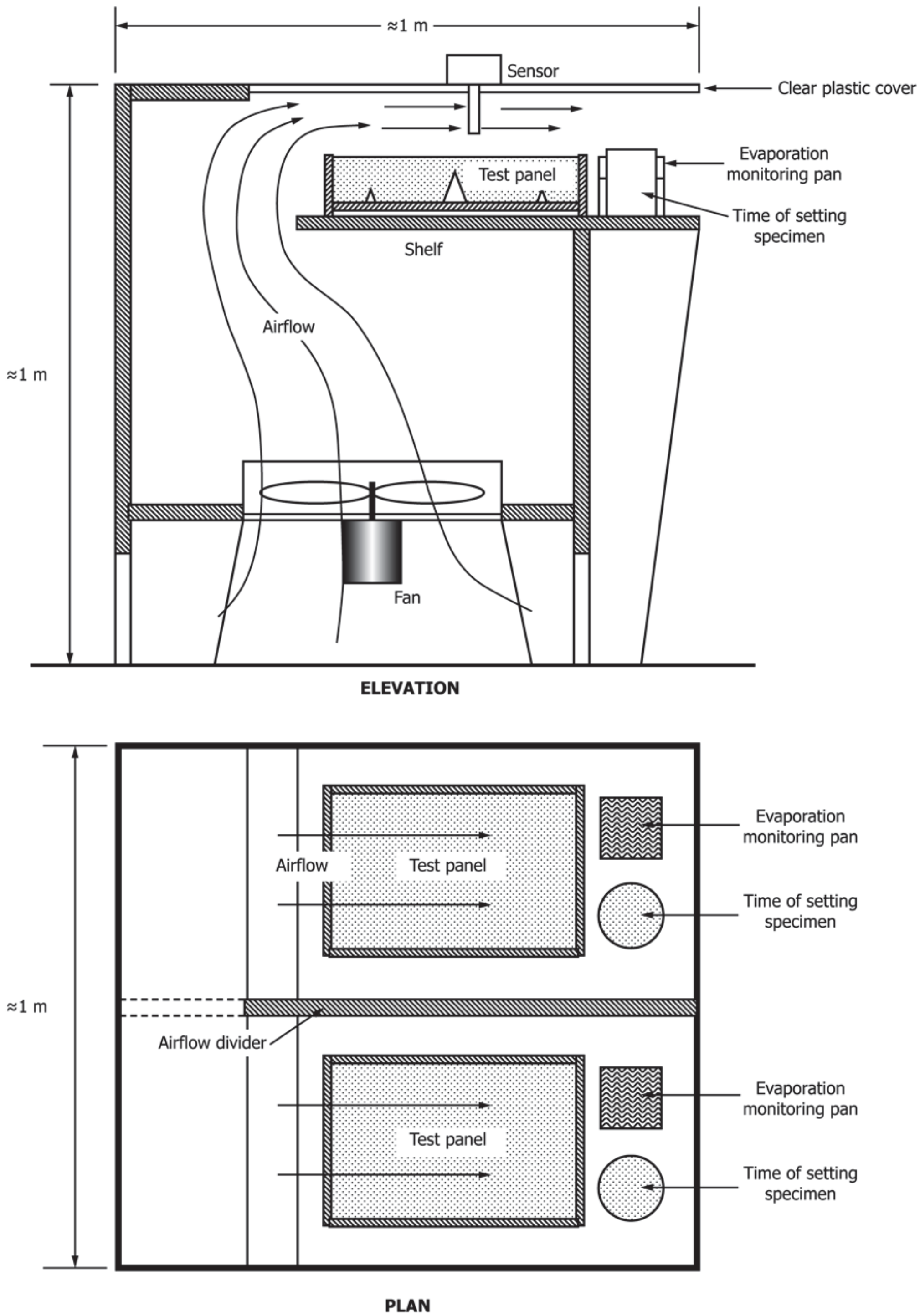

FIG. 2 Example of Fan Box to Maintain Environmental Conditions (2) (Not to Scale)

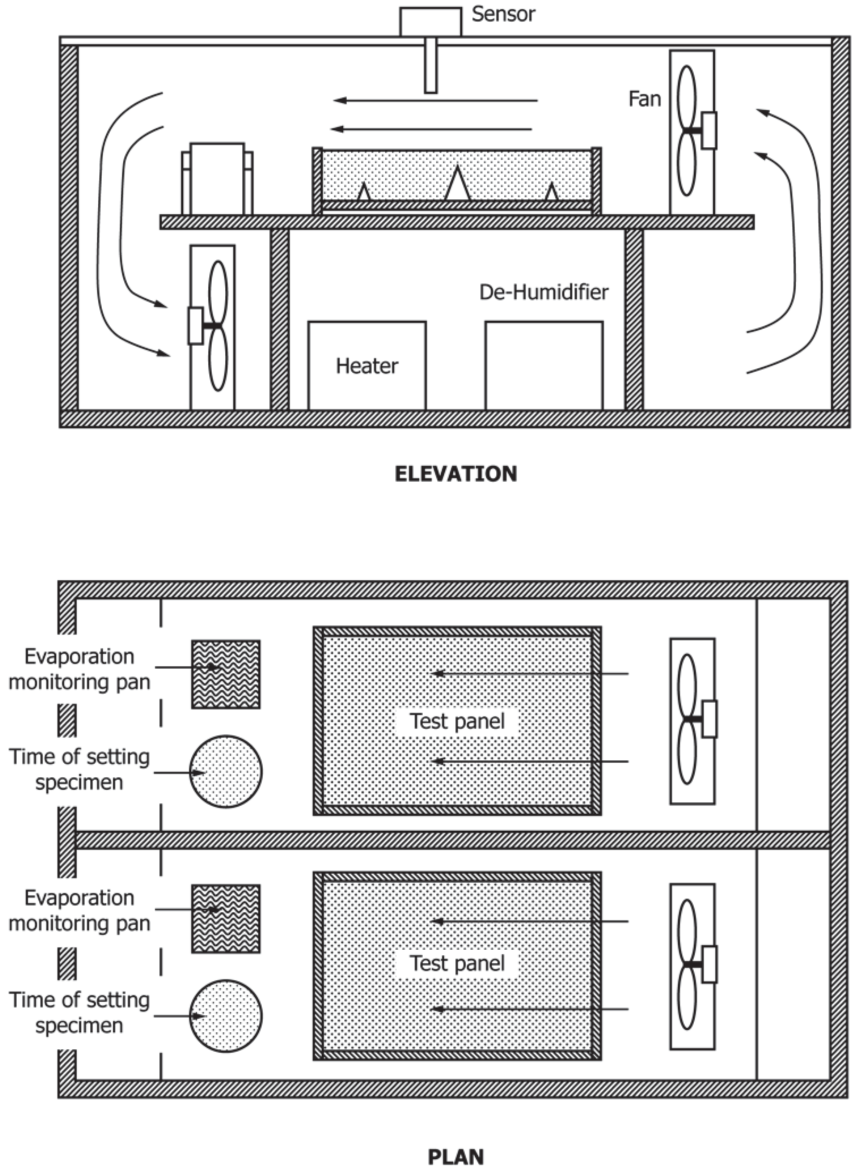

FIG. 3 Example of Chamber to Maintain Environmental Conditions (4)

specifier of tests, record the time at which cracking is first observed for each panel surface. Perform penetration tests at regular time intervals according to Test Method C403/C403M. Continue recording the environmental variables until the time of final setting.

7.8 The evaporation rate is determined by initially weighing the full monitoring pans at the start of the test and at 30-min intervals thereafter **(5)**. Record the mass loss to the nearest 5 g at each weighing. To determine the evaporation rate during each time interval, divide the mass loss between successive weighings by the surface area of the water in the weighing pan and the time interval between successive weighings (see Note 6). The test is not valid if the average evaporation rate is less than 1.0 kg/m^2·h.

NOTE 6—Adjustments to wind velocity should be made if necessary to maintain the evaporation rate at the required level. It is suggested that the monitoring pans be placed on scales in the air stream for continuous monitoring without periodic removal during testing. If this is not possible, the monitoring pan should be removed from the air stream, weighed, and returned to the air stream within 15 seconds.

7.9 After final setting occurs (use the later of the measured time of setting in the two specimens), record the atmospheric variables, stop the fans, record the time, and determine the total water loss from the monitoring pans. If panel moisture loss is to be determined, weigh the test panels in their molds. Store the panels in the laboratory at 23 ± 2°C and under plastic sheets to minimize evaporation until time of crack width measurement.

8. Quantification of Cracking

8.1 Quantify the amount of cracking by measuring crack widths at the surface of the panels 24 ± 2 h after mixing.

NOTE 7—Studies have shown that, when panels are covered with plastic, there is no appreciable change in average crack width from a time of six hours to 24 h after mixing **(3)**.

8.2 To avoid possible effects of panel boundaries on crack width, do not measure crack widths within 25 mm of test panel boundaries.

8.3 Measure the width of each crack along the cracking path over the stress riser in a progressive order from one side of the panel to the other. If a manual crack width measuring procedure is used, use a crack comparator or crack microscope to measure crack widths. Measure crack width to the nearest 0.1 mm at 10 ± 1 mm intervals along the length of the crack. Repeat the above procedure until all cracks have been measured. If an imaging analysis procedure is used for crack width measurement, record crack widths over the same measuring distance (see Note 8). Overlap between adjacent images shall be cut off to avoid duplicated measurements **(4)**. Record all crack widths to calculate average crack width.

NOTE 8—A grid mask can be used to sample crack widths at predetermined locations **(4)**.

8.4 Calculate the average crack width to the nearest 0.05 mm. If an average crack width of at least 0.5 mm is not observed on the control panels (average of at least two panels), with no single control panel under 0.4 mm average crack width, the test is not valid. Increase the evaporation rate to achieve this minimal average crack width, and repeat the test (see Note 10).

NOTE 9—Requiring a minimum crack width of the control panel will help to prevent marginal modifications to the concrete mixture from showing a statistically significant performance improvement, which may not be sufficient to control cracking under field conditions.

NOTE 10—Refer to ACI 305R **(1)** for guidance on how wind speed affects evaporation rate.

8.5 Calculate the crack reduction ratio (CRR) using the following equation:

$$CRR = \left[1 - \frac{\text{Average Crack Width of Fiber Reinforced Concrete Mixture}}{\text{Average Crack Width of Control Concrete Mixture}} \right] \times 100\% \quad (1)$$

TABLE 1 Single-Operator Average Crack Width Repeatability (22 Crack Width Measurements per Panel Using Manual Measurement Procedure)

NOTE 1—The results in this table correspond with the behavior of a mixture using a single type of fiber as described in Ref 3.

Mixture Identification	Fiber Volume	Number of Panels	Average Crack Width (mm)	Standard Deviation of Average Crack Width (mm)
A	0 % Fiber	6	0.67	0.04
B	0.05 % Fiber	4	0.44	0.05
C	0.10 % Fiber	4	0.33	0.05
D	0.15 % Fiber	4	0.08	0.04
E	0.20 % Fiber	2	0.03	0.02

9. Report

9.1 Report the following for each mixture tested:

9.1.1 The mixture proportions in kg/m^3 of water, cement (or cementitious materials): aggregates; admixtures in L/m^3; water-cement ratio (w/c) to the nearest 0.01; and slump in mm.

9.1.2 The fiber characteristics (if available) including fiber material, length, cross-sectional area, fiber shape, and addition rate in kg/m^3.

9.1.3 Length, depth, and width of panels in mm.

9.1.4 Cracking value of each panel as the average crack width to the nearest 0.05 mm.

9.1.5 The temperature, relative humidity, wind velocity, and measured evaporation rate during the test.

9.1.6 If required, the moisture loss of each panel in kilograms of water per square meter of surface (kg/m^2). Report the time interval between panel weighings.

9.1.7 The cracking reduction ratio (CRR) to the nearest percent (%).

10. Precision and Bias

10.1 *Precision*—A multi-laboratory study of precision has not been completed. Information on repeatability of this test method was derived from within-laboratory testing using a single operator and replicate panels **(3)** (see Practices C670). Table 1 shows the number of replicate panels, average of the average crack width, and standard deviation of the average crack width for control panels and panels made with concretes having different amounts of fiber. The standard deviation appears to be constant and is used as the measure of repeatability. When three panels were used to determine the Crack Reduction Ratio (CRR), the value of the single operator standard deviation was 4.6 %.

10.2 *Bias*—The procedure for measuring the cracking value has no bias because the cracking value is defined only in terms of this test method.

11. Keywords

11.1 crack width; evaporation; fiber-reinforced concrete; plastic shrinkage cracking; restrained shrinkage cracking

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SUMMARY OF CHANGES

Committee C09 has identified the location of selected changes to this specification since the last issue, C1579 – 06 (2012), that may impact the use of this specification. (Approved April 1, 2013.)

(1) Removed reference to ASTM C995 from Sections 2.1, 7.1, and 9.1.1.

APPENDIX B:

CONCRETE CRACKING RING TEST

Cracking Tendency Measurement due to Drying Deformation the First 24 Hours

CONCRETE CRACKING RING TEST:
CRACKING TENDENCY MEASUREMENT DUE TO DRYING DEFORMATION THE FIRST 24 HOURS

Key words: Concrete, cracking, shrinkage, drying

1 SCOPE

This test method covers determination of concrete cracking tendency at early ages. The test is performed on 3 restrained ring shaped specimen, exposed to an air stream of defined velocity, temperature and relative humidity, the first 24 hours after casting.

The principle of the test is that the concrete sample is cast around a restraining inner steel ring, causing a development of tangential stresses, that if sufficiently high may lead to cracking. The evaluation is based on characterization of the cracks in terms of average total area by the three samples.

The method is a modification of the Nordtest method “NT BUILD433”.

Problems with early-age shrinkage and cracking have become problematic. Conditions as reduced maximum aggregate size, increased amount of fines, presence of retarding admixtures, increased binder content and deficient covering and curing all contribute to this problem.

Most likely the cracking caused by drying shrinkage also are consisting autogenous shrinkage. Compared with autogenous shrinkage that generally develops uniformly through the concrete member, drying shrinkage occurs from the outside surface of the concrete inward, both causing cracks that develops rapidly and occurs when the cement paste is young and has poorly developed mechanical properties.

2 FIELD OF APPLICATION

With the “Concrete cracking ring test”, the plastic and hardening concrete cracking tendency can be used for an evaluated of different type of concrete exposed to early drying.

The test is only to be applied for laboratory use where the method information is relative and cannot predict the extent of cracking which might occur under prevailing conditions.

Maximum coarse aggregate size is 16 mm.

Concrete cracking ring test is preferable to be combined with:

- Volume or linear measurement of autogenous deformation, e.g. Concrete Digital Dilatometer (CDD) test for concrete.

3 REFERENCES

Sampling procedure: EN 12350-1, ASTM C172 or NT BUILD 191.

Cracking tendency test: NT BUILD 433

4 NOTATIONS

4.1 Definitions

Shrinkage; when the deformation is a contraction, it may be referred to as shrinkage, e.g. autogenous or drying shrinkage.

Autogenous shrinkage; the unrestrained, time-depending, bulk deformation of fresh and hardening sealed concrete at a constant temperature.

Chemical shrinkage; under sealed conditions, the cement paste hydration products occupy less space than the original reactants. Chemical is the major of factors causing the autogenous shrinkage.

Drying shrinkage; when water evaporates from the fresh and hardening concrete, tensile stress build up in the capillaries causing the concrete to contract. In early stages, drying shrinkage can be defined as plastic shrinkage.

4.1 Symbols

n number of cracks of each specimen.

l length of each crack, in millimeter [mm].

w each crack average width, in millimeter [mm].

A average total crack area calculated from two ore more samples, in sqr millimeter [mm^2].

t time after mixing, in hours [h].

Δm sample weight loss due to drying, in kilogram [kg].

E sample evaporation, in kilogram per sqr meter [kg/m^2].

v air velocity, in meter per second [m/s].

RH air relative humidity, in percentage [%].

T_a air temperature, in degree Celsius [ºC]

T_c concrete temperature, in degree Celsius [ºC]

5 METHOD OF TEST

5.1 Principle

When water evaporates from the fresh concrete the concrete tends to contract, and as contraction is restrained, tangential tension develops cross section of the ring specimen. The extent of cracking depends on both the magnitude of the tensile forces and on the strain capacity of the concrete.

The concrete is cast between two concentric steel rings with diameter 300 and 600 mm with a depth of 80 mm, see *Figure 1*. The steel rings have ribs attached to provide crack initiation and are fixed to a stiff base plate with a smooth surface. After casting, the ring specimens are positioned under air funnels with a 10 mm opening between the concrete surface and the funnel along the circumference of the outer ring. The funnel is shaped to provide equal wind velocity across the concrete surface of 4.5 m/s. The test is to be performed at stabile and constant environmental conditions, where one of the samples is to be placed on a balance.

The cracking tendency is evaluated from crack length and average width measurements on the concrete top surface.

5.2 Apparatus

Required equipment and apparatus for a typical test is:

- Thermal and humidity controlled room or chamber with a constant air temperature of T=20±1ºC and relative humidity of RH=40±3%. The conditions magnitude is not absolute, but they are preferable.
- 3 complete mould setup for ring specimen, as shown in *Figure 1*.
- 3 set of air funnels, including fan and ducting, as shown in *Figure 1*.
- Balance (load cell) with manual reading or automatic recording of weight changes.
- Devices and instrumentation for manual reading or automatic recording of:
  - air velocity
  - temperature and relative humidity of air
  - concrete temperature.
- Ruler or measuring wheel graded in 1/1 mm.
- Water level.
- Stopwatch, measuring 1/1 sec.

5.3 Preparation of test specimen

5.3.1 Mould

The inner and outer steel rings are fixed on a stiff base steel plate with a smooth surface. The steel rings are to be covered with a thin layer of form oil and the base plate is not be oiled.

5.3.2 Mix

Concrete constituents by dry weight shall be recorded. Max coarse aggregate size is 16 mm.

5.3.3 Mixing

Suitable concrete mixing method, mixer and volume is to be selected and documented. No standards are available.

5.3.4 Sample

The sample size is 17 liter (x3) and is to be collected in accordance with EN 12350-1, ASTM C172 or NT BUILD 191.

5.3.5 Casting

The concrete shall be sampled from the mixer immediately after the end of mixing period. The casting of 3 ring specimens shall be accomplished within 30-45 minutes after water addition.

The specimen must completely fill the mould (to the top of the inner and outer steel ring). If needed, compaction by vibration. Top surface are to be smoothed in equal manner.

5.4 Procedure

5.4.1 Starting the test

a) One of the specimens is to be placed on the balance.

b) Each specimens horizontal position are to be ensured (if unsure, use a water level).

c) One concrete temperature sensors is to be placed in the center of the mould cross section.

d) The air funnels are to be placed in such a way that the opening between the concrete surface and the funnel edge is uniform (10 mm) along the whole circumference of the outer steel ring.

e) The fans are to be started 55 minutes after water addition. Velocity over the concrete surface are to be ensured (4.5 m/s)

f) The recording phase (time t, concrete temperature T_c, specimen weight loss Δm, air temperature and humidity T_a and RH) to be started, 60 minutes after water addition.

The test is be performed in a thermal humidity stable and controlled room or chamber with an air temperature of 20±1ºC. and relative humidity of 40±3%

The starting procedure (a-d) is to be performed within 60 minutes from water addition, if not this time is to be noted.

5.4.2 During the test

If manual reading, continuously record the time t, concrete temperature T_c, specimen weight loss Δm, air temperature and humidity T_a and RH. Enough sampling frequency is to be selected for smooth curve of temperature and weight loss development (less then 1/2 hours interval).

Visual observation of specimens throughout the 24 hours can be made in order to describe the crack development. The type, orientation and time of occurrence of cracks can then be noted.

5.4.3 Finishing the test

Recording phase (t, T_c, Δm, T_a and RH) stops. Values are to be transferred to computer for calculation and evaluation.

5.4.3 Crack measurements

The ring specimens shall normally be examined after 24 hours exposure, and surface cracks with an approximate radial orientation shall be identified and marked in an adequate way. The average widths (w) and length (l) of each crack are to be measured and recorded. The width measurements shall be performed by the use of the magnifying glass and readings by interpolation to the nearest 0.02 mm. It is recommended that a lower crack limit is 0.05 mm. The main crack pattern of each ring can be recorded by photo or sketched by drawing.

The standard procedure also includes recording of weight loss and temperature development. These parameters give useful information about the evaporation of water, and serve as a control for identical tests as well.

5.5 Expression of results

The total crack area for each ring shall be calculated as accumulated sum of each average crack width multiplied by its length. The average total crack area (A) is expressed by the average areas for 3 rings, rounded to the nearest 0.1 mm, as:

$$A = \frac{\sum_{j=1}^{3}\left(\sum_{i=1}^{n}(l_i \cdot w_i)\right)}{3} \text{ [mm}^2\text{]}$$

The water evaporation (E) is calculated by the quote of weight loss (Δm) and ring surface area, as:

$$E = \frac{\Delta m}{0.212} \text{ [kg/m}^2\text{]}$$

The development of concrete temperature (T_c) and evaporation (E) with time (t) is to be presented graphically.

6 TEST REPORT

The report is shall include necessary information from among the following:

a) Document id (name, nr, test method, etc).

b) Date and time.

c) Performer id (name and address).

d) Test object id.

e) Purpose of test.

f) Concrete id (producer, recipe, etc).

g) Identification of the test equipment and instruments used.

h) Method of sampling.

i) Time from water addition to start/stop sampling and crack measuring.

j) Air velocity (v), temperature (t_a) and humidity (RH) during the test.

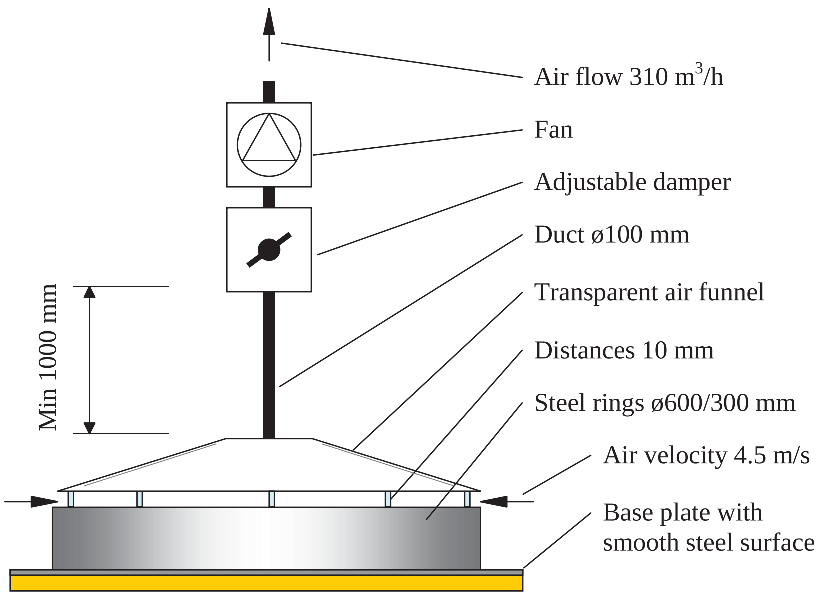
k) Test results: number of cracks (n), total crack area (A) and graphical presentation of concrete temperature and evaporation (t, T_c and E).

l) Relevant visually observations and personal judgments and interpretations.

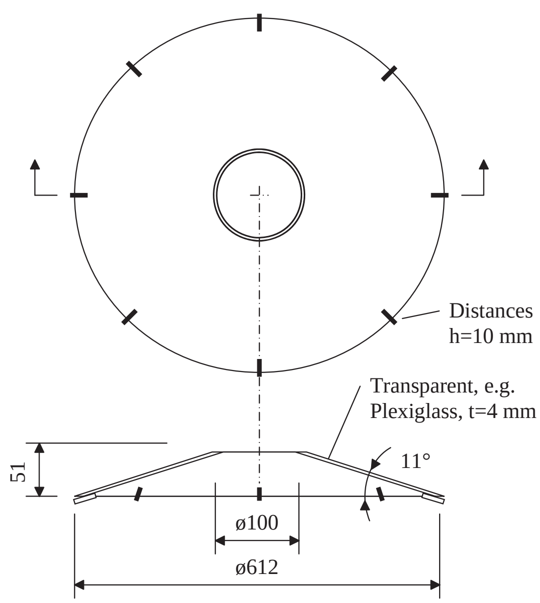
m) Any deviation from the test method.

n) Inaccuracy and/or uncertainty of test results.

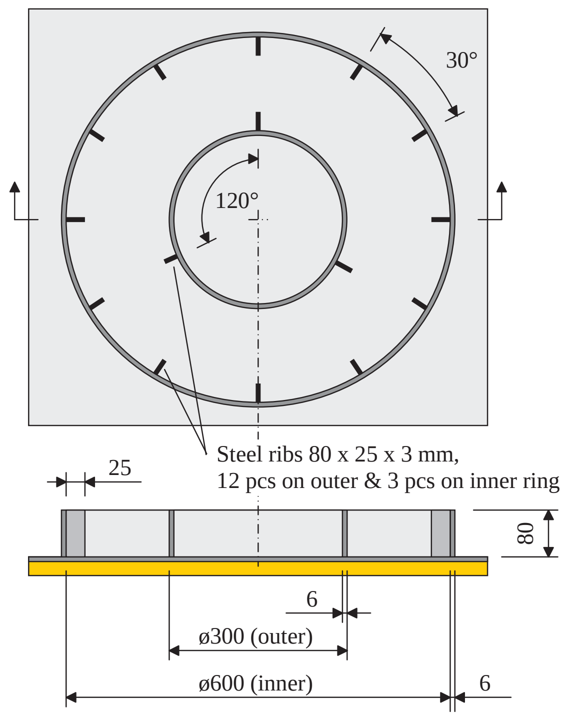
o) Date and signature.



Test arangement



Transparent air funnel



Ring mould setup

Figure 1. Principe of the concrete cracking ring test for cracking tendency measurement.

APPENDED PAPERS

PAPER I:

Plastic Shrinkage Cracking in Concrete: Research in Scandinavia

Sayahi, F., Emborg, M. and Hedlund, H. (2014), published in proceeding of the XXII Nordic Concrete Research symposium, Reykjavik, Iceland, August 13 – 15, 2014, pp. 351 – 354.

Plastic Shrinkage Cracking in Concrete: Research in Scandinavia

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ABSTRACT

As plastic shrinkage cracking still causes considerable repair costs annually, an understanding of the phenomenon is essential to prevent these damages in the future. In the paper, the status of present technology to avoid cracking is briefly reported through referring to research conducted in Scandinavia. In addition, on-going activities at LTU are described and future plan is demonstrated. Thus, experiments are performed on concrete slabs cast in rectangular moulds and cured at some variations of environmental conditions. The results will be used to find critical evaporation rate at very early age.

KEYWORDS: Plastic Shrinkage, Cracking, Concrete, Evaporation.

1. INTRODUCTION

Crack-free concrete structures are needed, in order to ensure high level of durability and functionality, since cracks accelerate the ingress of harmful materials that might cause damage in future (i.e. corrosion of the reinforcement). Plastic shrinkage cracking is the first type of cracks occurring directly after placing the concrete, sometimes even before the final setting /Schmidt & Slowlk 2013/. This type of cracking mainly occurs on horizontal concrete surfaces such as slabs, pavements, beams, etc. exposed to hot and/or windy conditions. Many factors affect the likelihood of plastic shrinkage cracking such as water-cement ratio, admixture, member size, fines content , concrete surface temperature and ambient conditions (i.e. relative humidity, air temperature and wind velocity) /Uno 1998/. All these factors influence the water evaporation rate from the freshly placed concrete surface which is considered as an indication of the possible beginning of the plastic shrinkage cracking /Uno 1998/.

2. PREVIOUS RESEARCH IN SCANDINAVIA

In order to obtain a better comprehension of the plastic shrinkage cracking phenomenon, various research have been performed world-wide and Scandinavia is not an exception. Researchers such as Hedin /1985/, Johansen and Dahl /1993/, Lund et al. /1997/, Hammer /1999/ and Esping and Löfgren /2006/ studied different aspects of plastic shrinkage cracking and prepared a strong launch platform for further investigations.

For example, ten laboratory experiments and two field trials conducted by Hedin in 1985 to investigate what type of curing best prevents plastic shrinkage in the newly cast concrete. It was stated that covering the concrete with plastic wrap and membrane, decreases the evaporation rate and consequently leads to a crack-free concrete.

Using the same setup, Lund et al. argued that lower water-cement ratio causes less bleeding water and thus, logically, increases the risk of cracking /Lund et al. 1997/. Also the evaporation rate was documented in the study.

In 1993, Johansen and Dahl preformed series of experiments in order to develop a method for determination of the cracking tendency of concrete at early ages. During the tests, fresh concrete was cast between two concentric steel rings. The specimen was then placed under an air funnel, to create an air stream with the required velocity over the fresh concrete surface /Johansen and Dahl 1993/. The crack tendency was then judged quantitatively at the end of the test (20 to 24 hours after casting) /NORDTEST NT BUILD 433, 1995/.

Hammer performed a set of experiments to study the relations between autogenous volumetric and linear shrinkage before and during the setting of paste-mortar-concrete, chemical shrinkage bleeding and concrete settlement. The objective was to obtain a reliable and meaningful method to measure the linear autogenous shrinkage of concrete /Hammer 1999/. Among other things it was observed that reabsorption of bleeding water which occurs around the setting is helpful from crack risk point of view /Hammer 1999/.

Esping and Löfgren studied the early age (less than 24 hours) autogenous deformation and pore-pressure development of Self-Compacting Concrete (SCC) and evaluated its crack tendency due to plastic shrinkage. This was done by exposing concrete specimens to early drying conditions (a modified NT BUILD 433). The experiments consisted of different SCC constituents and mix compositions e.g. water-cement ratio from 0.38 to 0.67, silica fume, and different admixtures /Esping & Löfgren 2006/. In addition, the experiments were repeated with standard concrete for comparison. According to the results, Esping and Löfgren argued that a high crack tendency occurs when there is a) a large amount of autogenous shrinkage (low w/c, silica addition, high fineness) b) retardation (retarder or high super plasticizer dosage) c) high water evaporation (low fineness or high w/c) d) low content of coarse aggregate /Esping & Löfgren 2006/.

3. EXPERIMENTS AT LTU

In order to practically study the phenomenon of plastic shrinkage cracking, laboratory tests have been conducted in the laboratory of Complab, Luleå University of Technology (LTU). The experiments were designed in order to monitor and understand the water evaporation rate in concrete slab under varying environmental conditions. Furthermore, how capillary pressure in the concrete develops and its relationship with plastic shrinkage cracking is a part of the project. Various concrete mixtures at different conditions will be tested to understand how the water evaporation rate and capillary pressure develops and influences the plastic shrinkage cracking.

For these experiments, a test rig (1200x400x90 mm) has been designed based on the experimental setups used by Hedin /1985/ and Lund /1997/, (see Figure 1). The frame is made of UPE80-beams placed on a 1 mm thick steel plate. It is possible to disassemble and reuse the frame after each test. Latex is used to seal the beam-plate and beam-beam interfaces. Rebars, 8 mm diameter, are installed inside the mould to create external constraint in the concrete. The rebars are fixed against 18 rods in total around the mould (6 rods along the long- and 3 rods along the short-side). Each rod penetrates the concrete by 60 mm.

The rig is placed on four load cells for continuous weight measurement. A 50 cm wide fan is used to produce wind with constant velocity on the slab surface varying from 0 to 7 m/s in different trials. A wind tunnel is place on the slab to conduct the wind over the surface. At the moment, two parallel rigs are used to be able to vary curing conditions etc. on exactly the same concrete mix.

Figure 1 – Test setup for plastic shrinkage crack experiments at LTU.

So far tests have been performed with CEM II Portland-limestone cement (Byggcement, Cementa) which is vastly used in standard concrete work such as house building nowadays. Water-cement ratio is 0.38 to reach a 28 days strength of 60 MPa alongside with a S4 slump (160-210 mm) / Lundström 2013/. It should be noted that the mentioned values represent the first tested mixture which may differ by the experiments progress in future.

The aggregates and cement are mixed together for 1 minute in a mixer with 50 litre capacity. Then, water and the super plasticizer are added to the mixture simultaneously. The concrete should be left to mix for 5 minutes. The final fresh concrete would be cast in the above described mould and compacted using a vibrator. At this stage the concrete slab surface should be treated and finished carefully in order to have a smooth surface.

Having prepared the surface, the wind tunnel is placed on the slab and the fan is set on the required speed. Documentation is performed on water evaporation, air temperature, concrete temperature (at 7 points), wind speed and relative humidity. Each specimen is exposed to the wind for at least 4 hours while the surface of the slab is carefully monitored to record the occurrence of possible plastic shrinkage crack initiation.

4. FINAL COMMENTS

In these experiments the total weight lost is considered to be the total water evaporation. By plotting the evaporation rate against time, effect of different factors on the evaporation rate can be understood. The plan is to perform this test for different concretes to achieve a clear picture regarding the critical water evaporation rate for cracking at different conditions. Furthermore, it is planned to include the capillary pressure measurement in future. Results of the above mentioned tests, can prepare a useful database for further investigations regarding plastic shrinkage cracking in concrete. Outcomes of these experiments, will be compared with full scale tests and the currently used method such as nomograph presented by Uno /1998/. Based on such a comparison, further investigation opportunities may emerge.

ACKNOWLEDGMENT

The authors would like to appreciate the support they received from the Development Fund of the Swedish Construction Industry, SBUF, as well as the personnel of Complab at LTU.

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PAPER II:

Plastic Shrinkage Cracking in Concrete: State of the Art

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Plastic Shrinkage Cracking in Concrete: State of the Art

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ABSTRACT
As plastic shrinkage cracking can dramatically reduce the durability of a concrete member and causes considerable repair costs annually, a comprehensive understanding of the mechanism of the phenomenon is essential to prevent these damages in future. In this paper, an overview is given on the mechanism of plastic shrinkage crack formation and the status of present technologies avoiding the cracking are reported through referring to previously conducted research and observations.

Keywords: Plastic Shrinkage, Cracking, Concrete, Evaporation, Capillary pressure.

1. INTRODUCTION

Crack-free concrete structures are needed in order to ensure high level of durability and functionality, since cracks accelerate the ingress of harmful materials that might cause damage in future, e.g. corrosion of the reinforcement [1]. Plastic shrinkage cracking of concrete is often the first type of cracks occurring shortly (within the first few hours) after placing the concrete, even before initial setting [1-4]. As known also settlement cracks can occur very early. According to ACI 305R [5]: "Plastic shrinkage cracking is frequently associated with hot weather concreting in arid climates. It occurs in exposed concrete, primarily in flat work but also in beams and footings and may develop in other climates whenever the evaporation rate is greater than the rate at which the water rises to the surface of recently placed concrete by bleeding". It is thus understood that this type of cracking, mainly occurring on horizontal concrete elements with large surface to volume ratio (such as slabs, pavements, beams, etc.), can dramatically affect the aesthetics, durability and serviceability of the structure [6, 7].

The main reason behind plastic shrinkage cracking is considered to be rapid and excessive surface water evaporation of the concrete element in the plastic stage (freshly cast concrete) which in turn leads to the so-called plastic or capillary shrinkage [2-5, 8-17]. Consequently, many factors affect the likelihood of plastic shrinkage crack formation such as water-cement ratio, admixture, member size, fines content, concrete surface temperature and ambient conditions (i.e. relative humidity, air temperature and wind velocity). All these factors influence the water evaporation rate of the concrete which is considered, among others, as an indication of the possible beginning of the plastic shrinkage cracking [18]. As long as the evaporation rate is less than the bleeding rate, a thin water film covers the surface of the concrete. Soon after the disappearance of this thin water layer, capillary pressure inside the concrete increases, which results in the so called plastic shrinkage. It should be mentioned here that the bleeding can be very small or not existing at all for concretes of low water/cement ratio, e. g. those designed for fast drying through self-desiccation..

If the concrete member is restrained in any way (e.g. due to reinforcement, change of sectional depth, difference in shrinkage in different parts of the concrete, friction of the mould, etc.) , the developed shrinkage can cause tensile strain accumulation, starting from the concrete surface. When the tensile strain exceeds the tensile strain capacity of the concrete, which at early ages is very low, cracks start to form [19]. In many cases, plastic shrinkage cracks are so thin (sometimes invisible to an unaided eye) which can be overlooked or covered by the surface finishing [2]. However, later on phenomena such as external loading, thermal strain, or drying shrinkage can widen the crack which as mentioned earlier negatively influences the serviceability of the concrete structure.

Plastic shrinkage cracking, in general, is a complex combination of interdependent variables which can facilitate or prevent the phenomenon under different circumstances. Thus, studying plastic shrinkage cracking requires a high level of persistence and intense theoretical and experimental investigation.

In this paper, the phenomenon of plastic shrinkage cracking in concrete is investigated and an attempt is made to reach a comprehensive perspective of the formation process and mechanism. In addition several variables such as water/cement ratio, thickness of the concrete section, fines content, additives, and fibres are briefly described. This research is based on the achievements reported by several researchers around the world and aims to present a state of the art in order to make plastic shrinkage cracking in concrete clearer and more understandable. The work intends to constitute a base of future research at Luleå University of Technology.

2. MECHANISM OF PLASTIC SHRINKAGE CRACKING

In order to gain a general comprehension of the plastic shrinkage cracking phenomenon, initially, it is important to have a picture, as clear as possible, regarding the mechanism of plastic shrinkage crack formation. In Fig.***Figure*** 1 (quoted from [6]), the process of plastic shrinkage crack formation is schematically explained. Based on the interaction between the plotted lines (factors), various milestones (i.e. drying time, air entry time, crack onset time, etc.) can be defined.

After placing the concrete in its mould, if not a high performance concrete or similar is used, a thin film of water covers the surface and an interconnected pore system, completely filled with water is formed [2]. Shortly later the drying time (TD) is reached when the water evaporation rate exceeds the bleeding rate of the concrete (see Fig.1). In this case the thin water film is disappeared due to evaporation and the water in the pore system starts to evaporate [20]. This moment is the onset of capillary pressure rise which converts it from a compressive pressure to a tensile pressure. The reason that capillary pressure is compressive before drying time is the existence of the internal water pressure in the concrete [20]. The capillary pressure keeps increasing until air breaks through the pore system, starting from the largest pores. This time is defined as the air entry time [17]. Consequently, the capillary pressure drops down suddenly and dramatically since the paste can no longer resist the tensile capillary pressure. Value of the capillary pressure at the air entry time is critical since the empty pores form weak points at the concrete surface which can be the origin of strain localization and cracking [2].

Based on the above, plastic shrinkage cracking is mainly related to the evaporation rate and bleeding rate of the concrete. These factors in addition to capillary pressure and tensile strain play the key role in the mechanism of plastic shrinkage cracking [2, 6, 18, 21]. These parameters are discussed briefly in the following sections.

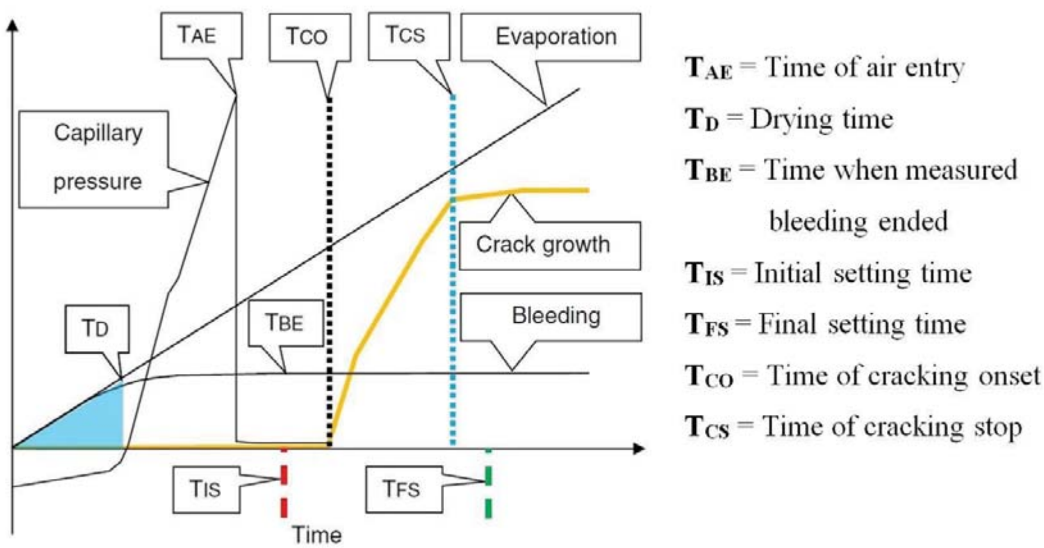

Figure 1 - Typical behaviour of plastic shrinkage crack [6]

3. EVAPORATION

The evaporation is considered as an indicator for the probability of plastic shrinkage cracking onset in freshly placed concrete. For instance, according to ACI, precautions must be taken when the water evaporation rate is equal to or more than 1.0 $kg/m^2/hr$ [5]. Nevertheless, some experimental results show that this value may be too high for some modern concrete compositions, i.e. plastic shrinkage cracking may occur at evaporation rate of 0.2 $kg/m^2/hr$ under hot weather conditions [12].

Water evaporation in concrete occurs due to a) heat energy absorption into the water, e.g. air temperature, concrete temperature, solar radiation; b) low humidity, i.e. the ambient pressure is less than that in the water [18]. Accumulation of escaping water molecules above the water surface increases the humidity and consequently decreases the evaporation, especially when the concrete perimeter is closed. Thus, wind can accelerate the process as it removes the escaping water molecules.

As can be comprehended from the above, the environmental factors that can highly influence the water evaporation rate are air temperature, concrete (water surface) temperature, wind and humidity. These factors are used in the ACI nomograph for estimating rate of surface water evaporation in concrete (see Fig.2). The outcome of this nomograph is a value for the evaporation rate of the concrete, in which provides an indication of the possible onset of plastic shrinkage cracking [18]. This nomograph was first developed by Bloem in 1960 [22] who in turn used the numerical values presented in a table by Lerch in 1957 [3]. The values in the table were derived using a formula presented by Menzel in 1954, expressed as Eq.1 (only available in imperial unit system)[23]:

$$W = 0.44(e_0 - e_a)(0.253 + 0.096\,V) \qquad (1)$$

where:
W = weight (lb) of water evaporated per square foot of surface per hour ($lb/ft^2/hr$),
e_0 = pressure of saturated vapour at the temperature of the evaporating surface, (psi)
e_a = vapour pressure of the ambient air, (psi)
V = Average horizontal air and wind speed measured at about 20 inches (500 mm) above the concrete surface, (mph).

In 1998, based on Menzel's formula, Uno [18] proposed a single operation equation to predict the water evaporation rate. The new formula does not use vapour pressure as input since a temperature-vapour pressure relationship has already been incorporated in the formula. The correlation coefficient of this relationship is 0.99 for the temperature range 15 to 35˚C [18]. The formula is expressed as:

$$E = 5([T_c + 18]^{2.5} - r\ .\ [T_a + 18]^{2.5})(V + 4) \times 10^{-6} \qquad (2)$$

where
E = water evaporation rate, ($kg/m^2/h$)
T_c = Concrete (water surface) temperature, (˚C)
T_a = air temperature, (˚C)
R = relative humidity, (%)
V = wind velocity, (km/hr).

This formula is widely used since the establishment. Comparison between Menzel and Uno's formula shows almost complete accordance in the results. In addition both formulas give almost similar evaporation rates to those extracted from the ACI nomograph. However, even if the water evaporation rate is accurately determined based on the above mentioned methods, still there is no guarantee that it can be applicable and reliable indicator of the cracking onset. That is due to the fact that, as mentioned earlier, the evaporation rate has to exceed the concrete bleed rate in order to cause plastic shrinkage [25].

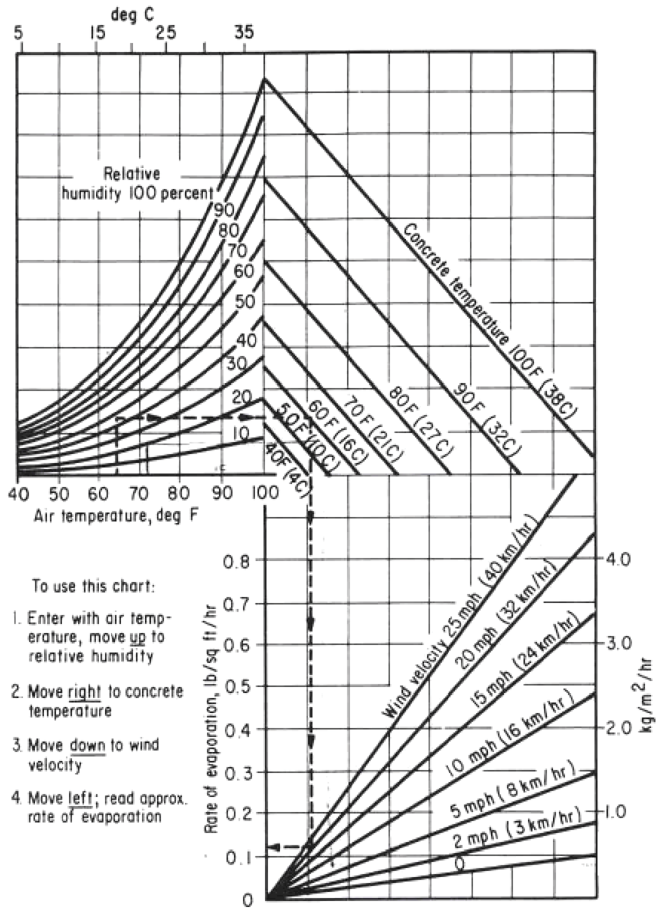

Figure 2 – ACI nomograph for estimating surface water evaporation rate of concrete i e. the "ACI Hot Weather Concreting Evaporation Nomograph" [5].

4. BLEEDING

Bleeding is defined as the ascending of the mixing water to the concrete surface. Typically, it occurs as the result of settlement and consolidation of freshly placed concrete under the gravitational force [26]. It occurs due to the inability of the solid particles to retain the water during the settlement. There are two independent driving forces which cause bleeding in concrete: the gravity which settles the solid particles of the concrete mixture, and the capillary pressure (suction) which occurs after the thin water layer on the surface has disappeared [16]. Bleeding rate can be measured experimentally using some standard methods such as the Australian standard [27] or according to ASTM C232/C232M [28].

In general, bleeding depends on the water/cement ratio, particle size distribution, viscosity of the concrete and the rate of hydration [6]. In addition, the depth of the concrete member can influence the bleeding rate [2]. Bleeding typically stops when the hydration products are abundant enough to prevent any further concrete settlement, which is the description of the state at the initial setting time of the concrete [29].

The assumed range of bleeding rate for concrete has decreased during the past century. Until 1960, it ranged from 0.5 to 1.5 $kg/m^2/h$ [16, 18]. However, in modern concretes, bleeding rate is considerably decreased to less than 1 $kg/m^2/h$ [16]. The reason lies in the general desire of gaining less bleed rate in order to achieve higher mechanical properties and less permeability in the modern concretes through lowering w/c ratio and increasing fine cement, fly ash and silica fume content in the mixture. The final product then, is a concrete with extremely low or even zero bleeding rate [30].

Although a certain level of bleeding might be desirable in order to replace evaporated water and keep the surface wet, it should be noted that excessive bleeding in turn, may cause various damages as well. These damages include plastic settlement cracking, surface laitance formation, longer finishing time, strength decrease and lower bonding between the solid particles [12, 16].

5. CAPILLARY PRESSURE

Capillary pressure (also referred to as matric suction, capillary tension or capillary suction) is as discussed earlier the origin of plastic shrinkage cracking. It is highly influenced by the water evaporation rate of the concrete. Therefore, capillary pressure can be considered as another indicator for the risk of shrinkage cracking onset.

5.1 Capillary pressure build-up mechanism

Plastic or capillary shrinkage is a result of a physical process which builds up negative pore pressure in the liquid phase of the cementitious material [2, 11]. As mentioned before, after casting the concrete, a thin plane film of water covers the surface of the concrete member and an interconnected pore system, completely filled with water is formed (Fig.3, Level A). As long as the evaporation rate is less than the bleeding rate, the surface remains covered by this thin water layer. However, the thickness of this layer decreases gradually, as a result of evaporation. Once the water layer disappears, the adhesive force and surface tension of water form menisci between the solid particles of the paste (Fig.3, Level B and Fig.4). These menisci cause negative pressure (tensile capillary pressure) in the concrete pore system. The description of this phenomenon lies in the Young-Laplace equation when the pores are assumed perpendicular to the concrete surface:

$$P = -\frac{2\gamma}{R} \cdot \cos\theta \tag{3}$$

where
P= pressure in the pore liquid, (Pa)
R = radius of the meniscus, (m), see Fig.4
γ = surface tension of the pore liquid (0.073 N/m for water)
θ = wetting angle, (deg.).

Cementitious materials are considered as siliceous materials i.e. full wetting material. In such material the wetting angle is 0.

The negative capillary pressure, applies inward force on the solid particles at the concrete surface. As the evaporation continues, the radius of the menisci in the pore system gradually decreases (Fig.3, Level C). Consequently, the capillary pressure keeps rising, causing contraction of the material. So far the contraction induced volume change approximately equals the volume of the evaporated water [17].

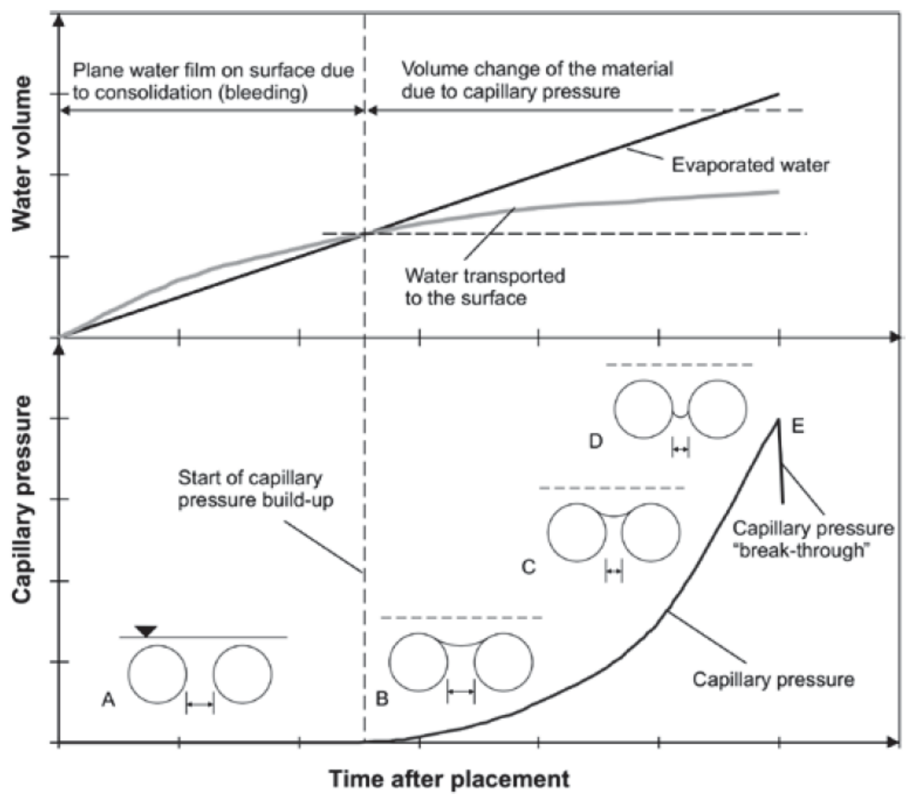

Figure 3 – Mechanism of capillary pressure build-up. The upper part of the figure shows evaporation and bleeding vs. time after placement (see also Fig. 1) [2].

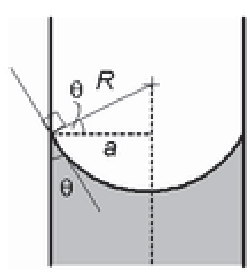

Figure 4 – Water meniscus in a pore.

As the capillary pressure increases, the radius of the meniscus decreases until it becomes equal to the minimum radius of the associated pore (Fig.3, Level D). The rise of the capillary pressure continues until at a certain value, the menisci break and let air penetrates the pore system (Fig.3, Level E). Once this happens, the capillary pressure dramatically drops down to almost zero i.e. it breaks down. The moment when capillary pressure breaks down and air penetrates into the pore system is called air-entry time.

It should be noted that due to the irregularity of particle arrangement in the concrete paste, air entry does not occur simultaneously in all pores [17]. In other words, air entry is rather a local event than a universal one. Therefore, different values for maximum capillary pressure may be measured in different parts of the concrete member. For example, Slowik [29] in 2008 performed an experiment on cement paste samples, using two pressure sensors in different locations. Each sensor measured different maximum capillary pressure (Fig.5). Thus, the maximum capillary pressure at a certain location does not represent the absolute maximum capillary pressure in the concrete. In addition, the capillary pressure may break down if the sensor tip penetrates an air bubble inside the concrete [17].

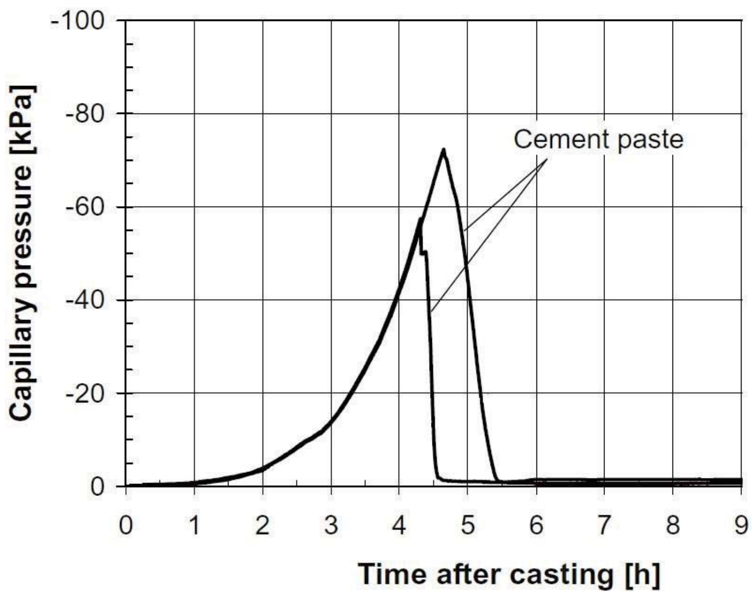

Figure 5 – Difference in maximum absolute capillary pressure in different locations [29].

Based on Carman [31], an equation was proposed by Powers [25] for determining maximum capillary tensile pressure in concrete, which was modified by Cohen [10]:

$$P = 1\times 10^{-3}\,\frac{\gamma \cdot S}{w/c} \qquad (4)$$

where
P= capillary tensile pressure, (MPa)
γ = surface tension of the pore liquid (0.073 N/m for water)
S = mass specific surface area of cement, (m^2/kg)
w/c = water/cement ratio by mass, (-)
The constant 10^{-3} has the dimension mass density (kg/m^3).

According to Eq.4, capillary pressure (P) is directly proportional to γ and S, and inversely proportional to w/c ratio. It means that keeping other variables constant, concrete with higher w/c ratio and lower γ and S is less suspected to experience plastic shrinkage cracking [16].

Furthermore, based on Eq.4, assuming constant γ and w/c ratio, capillary pressure (P) is directly proportional to mass specific surface area of cement (S). In other word, maintaining all conditions similar, any difference in plastic shrinkage characteristics (i.e. strain and cracking) would be due to the difference in surface area or particle size of the solid material [10]. This was also observed in Eq.5 proposed by Pihlajavaara [32] to determine the capillary pressure in concrete with spherical non-porous solid aggregates:

$$P = 2.6\times10^{-7} \cdot \gamma \cdot S \cdot \rho \qquad (5)$$

where
P= capillary tensile pressure, (MPa)
γ = surface tension of the pore liquid (0.073 N/m for water)
S = mass specific surface area of cement, (m^2/kg)
ρ = solid density of cement, (kg/m^3)
The constant 2.6×10^{-7} is dimensionless.

The maximum absolute capillary pressure, P, is considered critical since - after breaking down - creates weak points at the surface of the concrete. If the concrete is restrained, these weak spots, eventually, may be origins of strain localization and crack initiation along a line which connects them.

Based on the above mentioned facts, the capillary pressure in the concrete must kept less than the air entry value to prevent any strain localization and cracking onset. This typically takes place through preventing the surface water evaporation

5.2 Capillary pressure measurement

Capillary pressure in concrete is typically measured using pressure sensors such as those showed in Fig. 6. The tip of the sensor is filled with water which allows in-situ negative fluid pressure measurement. The tip of the sensor should penetrate the concrete by about 50 mm. In this case, the weight of the sensor is supported by the sensor tip. A recording device, then, collects all the data from the pressure sensors, which makes it possible to plot them versus time in a diagram. Both wired and wireless sensors are now available on the market.

6. TENSILE STRAIN

As previously mentioned, increasing capillary pressure leads to plastic shrinkage in the concrete. If the concrete is restrained (e.g. due to reinforcement, change of sectional depth, difference in shrinkage in different parts of the concrete, friction of the mould, etc.), this plastic shrinkage causes mechanical tensile strain (i.e. if the plastic shrinkage can develop freely, it will not induce any cracking). On the other hand, experiments have shown that strain capacity reaches its lowest value around the initial setting time of the concrete (see Fig.7) [6]. Once the strain capacity is less than the mechanical tensile strain, the concrete starts to crack.

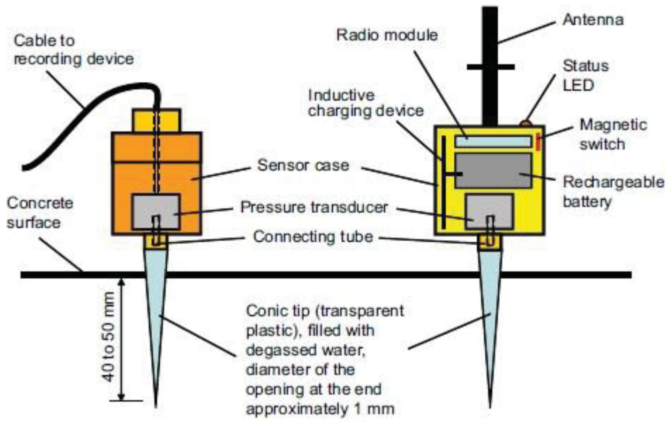

Figure 6 – Wired and wireless pressure sensors [2]

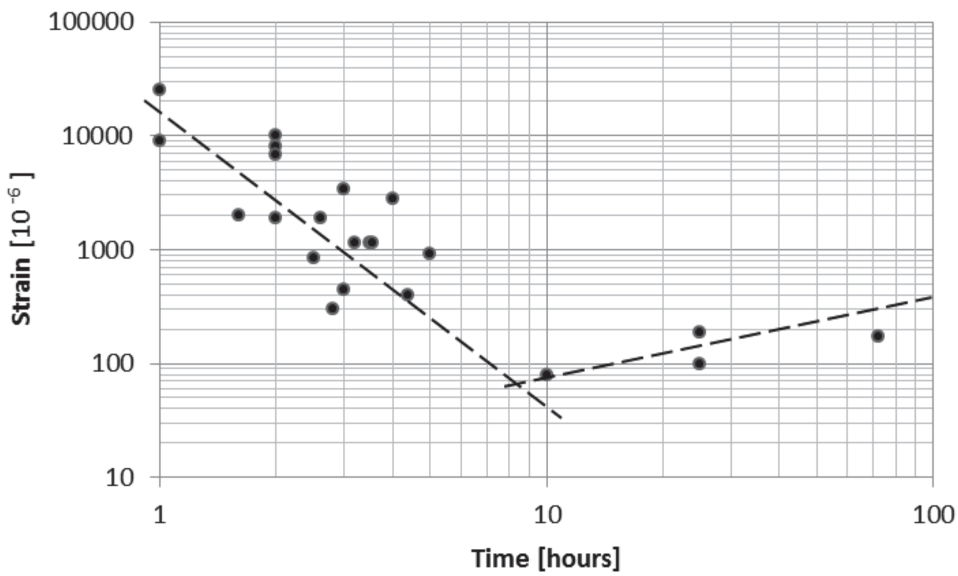

Figure 7 – Tensile strain capacity of fresh concrete [6].

As it was mentioned in section 2, plastic shrinkage cracks, typically, are visible after the initial setting time of the concrete (see Fig.1), which confirms the above mentioned fact. Hence, plastic shrinkage induced tensile strain can be another indicator of the cracking risk.

Several researchers have taken this fact into account and developed models to estimate the plastic shrinkage cracking risk based on the tensile strain in the concrete. Boshoff [6] in 2013, proposed a so-called "PShC severity model" to predict the plastic shrinkage cracking degree:

$$PShC = ER \times t_{set} - W_{bl} \qquad (6)$$

where
ER = evaporation rate, (kg/m^2/h)
t_{set} = the time between casting and the initial setting time, (hr)
W_{bl} = the total bleed water, (kg/m^2).

According to this model, the severity of plastic shrinkage cracking is dependent on the plastic shrinkage strain which is directly related to the rate of water evaporation, hardening time of the concrete (initial setting time) and bleeding characteristics [6]. In other word, it relates the severity of plastic shrinkage cracking to the amount of the evaporated water (total amount of evaporated water, minus the bleed water) from within the concrete, between the casting and initial setting time [6].

7. MAIN FACTORS AFFECTING PLASTIC SHRINKAGE CRACKING

So far, the main parameters in the mechanism of plastic shrinkage formation, (i.e. evaporation rate, bleeding rate, capillary pressure and tensile strain) and the relation between them have been briefly described. Fig. 8 is an attempt so summarize the parameters mentioned and the way they are linked together. Nevertheless, there are many factors which can affect plastic shrinkage cracking. A deep comprehension of the way these factors influence the whole cracking process can lead to invention of new crack prevention methods. Some of these factors are briefly described in the following , including water/cement ratio, depth of the concrete section, additives, fines content, fibres and curing measures.

7.1 Water/cement Ratio

Water/cement ratio plays a key role in plastic shrinkage cracks formation. Higher w/c ratio means more bleeding water and vice versa. Thus, in case of high w/c ratio, it takes longer time for the surface water layer to disappear due to evaporation and consequently delays the capillary pressure build-up in the pore system.

It is known that a lower w/c ratio causes less bleeding water and thus increases the risk of cracking [33]. On the other hand w/c ratio has an inverse relation with the concrete strength as higher w/c ratio causes lower concrete strength and vice versa. Research has shown that high-strength concrete mixtures (containing more cement) have low bleeding rate and subsequently higher risk of plastic shrinkage cracking [34]. Thus, optimizing the w/c ratio can be a method to avoid plastic shrinkage crack formation. If high-strength concrete is not necessary, it may be a good idea to use higher w/c ratio. However, it should be noted that very high w/c ratio can dramatically reduce the durability and serviceability of the concrete member.

7.2 Depth of the concrete section

A deeper concrete member typically experiences more settlement, since it contains more settling solid particles. Correspondingly, for higher w/c ratios, the bleeding capacity of the member is higher resulting in more bleed water accumulation on the surface. This means that the surface water layer evaporation takes longer time in comparison, causing delay in capillary pressure build-up. Consequently, it can be concluded that a deeper concrete section is less prone to plastic shrinkage cracking [8, 35]. However, due to the high degree of settlement, the concrete may be vulnerable to settlement cracking typically formed above the reinforcement bars, which may facilitate the ingress of chlorides and other harmful materials.

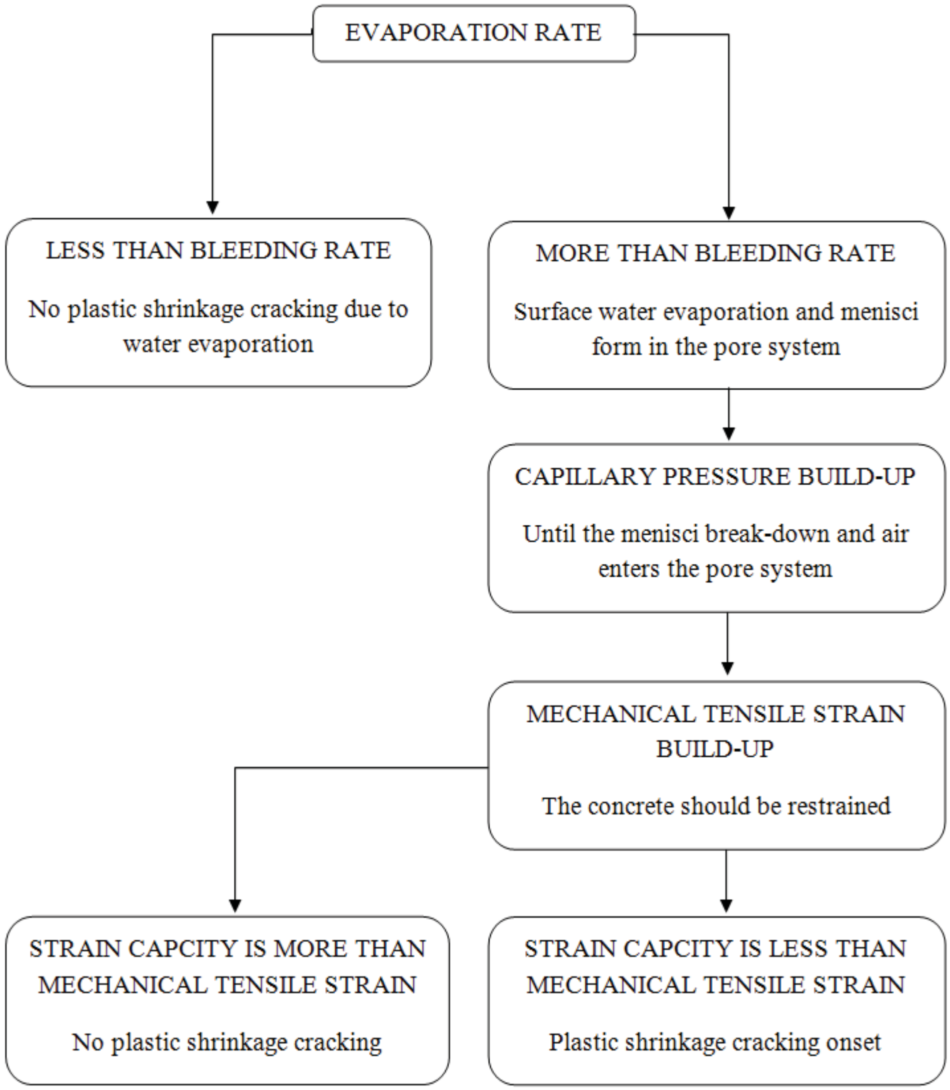

Figure 8 – Plastic shrinkage cracking flowchart.

7.3 Additives

Several research studies have been carried out to find new admixtures in order to reduce the plastic shrinkage of concrete. These admixtures show high practicality in reducing evaporation rate, settlement, negative capillary pressure and plastic shrinkage formation. For instance, it has been concluded that cellulose-based viscosity modifying agent (stabilizer) causes reduction of the evaporation rate [36].

Moreover, accelerators and retarders have a strong influence on plastic shrinkage cracking. Some experiments [20, 37] showed that accelerator admixtures cause higher plastic shrinkage and total crack area, while retarders act contrary. However, other experiments [15, 38] showed that excessive usage of retarder admixtures may increase the risk of plastic shrinkage cracking due to the slower strength gain of the concrete.

On the other hand, superplasticizers reduce the need for water in the concrete mixtures (less bleed water at the surface). This reduction of surface water may however not increase the risk of cracking, as the superplasticizer modifies the surface tension and prevent or delays the onset of plastic shrinkage crack formation [39].

7.4 Fibres

Fibres (steel and/or polypropylene) have often been recently used in concrete mixtures aiming at lowering the risk of plastic shrinkage cracking, through stitching the concrete surface particles together. For instance experimental results presented by Sivakumar and Santhanam [7] show that a combination of steel and polypropylene fibres (hybrid fibres), can reduce the width of the plastic shrinkage crack up to 55% in comparison to concrete mixture without fibres usage.

However, the only problem is that although the crack width was lower, parallel cracks were formed in the main crack's surroundings. This phenomenon can be due to the transfer of the shrinkage stresses, through the fibres, to the surrounding areas. The number of these parallel cracks could be reduced in case of steel fibre usage. The reason lies in more fibre availability in case of hybrid usage compared to the steel fibre system (due to the lower density of polypropylene fibre in comparison to steel fibres), which facilitates the shrinkage stress transfer. Nevertheless, hybrid fibres show a great enhancement in relation to reducing plastic shrinkage cracks [7].

7.5 Fines content

Fines (such as fly ash, silica fume, slag, etc.) induce greater surface area to adsorb water. Consequently, the water that is supposed to be transported to the concrete surface will be adsorbed on the fine particles, resulting in lower bleeding rate.

Cohen et al. [10] concluded that higher surface area of the particles leads to higher tensile capillary pressure and eventually higher probability of plastic shrinkage crack formation. Moreover, experiments performed by Esping et al. [15] showed that silica fume increases the crack tendency in the concrete. Thus, using high proportion of fine material in the concrete mixture is not favourable in relation to plastic shrinkage cracking.

7.6 Curing measures

Plastic shrinkage cracks can be avoided through several curing measures applied on the concrete after casting. Since the main reason behind this phenomenon is water evaporation, curing measures in general aim to eliminate or reduce the evaporation of the surface water. For example covering the concrete with plastic sheet, decreases the evaporation rate and consequently leads to a crack-free concrete [40]. In another case, experiments have shown that evaporation of the surface water can be suppressed through spraying aliphatic alcohols over the fresh concrete surface [41].

Moreover, in some cases curing the concrete takes place through replacing the evaporated surface water (rewetting). For example, fogging the freshly cast concrete surface, on one hand, reduces the evaporation rate through increasing the ambient relative humidity, and on the other hand, replaces some lost surface water due to evaporation [17].

In addition to the above, using a wind breaker to prevent or reduce the air flow over the concrete surface can be another way to reduce the evaporation of the surface water [18].

8. CONCLUSION

Plastic shrinkage cracking is a complex interaction of several variables that may change in different circumstances. These variables have direct influence on the evaporation and bleed rate of the concrete which subsequently affect the capillary pressure and tensile strain at the early age. The explanations offered in this paper for the plastic shrinkage cracking mechanism and the role of each variable in the process may facilitate gaining a comprehensive understanding of the phenomenon. Moreover, knowing the influence of each variable can lead to innovation of new crack preventive measures.

Despite of the general consensus on the major role of water evaporation in the plastic shrinkage crack formation, not all the cracking incidents are explainable based on that. This illustrates the incompletely understood aspects of the whole process. The inter-connection and complexity of the different variables need to be explored. Thus, in the future, emphasis should be on documenting the various factors through laboratory tests under controlled conditions.

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PAPER III:

Plastic Shrinkage Cracking in Self-Compacting Concrete: a Parametric Study

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PLASTIC SHRINKAGE CRACKING IN SELF-COMPACTING CONCRETE: A PARAMETRIC STUDY

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Abstract
Plastic shrinkage cracking, often the first type of cracks occurring even before initial setting, causes enormous expenses for the building industry annually. The main reason behind the phenomenon is believed to be rapid and excessive surface water evaporation of the concrete element in the plastic stage which in turn leads to the so-called plastic or capillary shrinkage. These cracks mainly occur in horizontal concrete elements with large surface to volume ratio (such as slabs, pavements, etc.). This paper reports results from experiments performed, using ring test method (NORDTEST-method NT Build 433). During the experiments, influence of water-cement (w/c) ratio, cement type, coarse aggregate content and super plasticizer dosage was investigated. Moreover, effort was made to explain the difference in cracking tendency of different concretes based on water evaporation rate and capillary pressure. It seems that various parameters have different influences on the cracking tendency, the evaporation rate, as well as the hydration rate and capillary pressure. Although, capillary pressure is local and its maximum value differs in different locations, it seems that its development rate, especially in the first few hours, is almost identical everywhere in the specimen. This may be used as a plastic shrinkage indicator.

Keywords: Plastic Shrinkage, Cracking, Evaporation, Capillary pressure, Dormant period, NORDTEST-method NT Build 433.

1. Introduction

Plastic shrinkage cracking in concrete is the first type of cracks occurring within the first few hours after casting, even before the initial setting. Horizontal concrete elements with large surface to volume ratio (e.g. slabs and pavements) are prone to this type of cracking. It accelerates the ingress of harmful materials that might cause damage in future, e.g. corrosion

of the reinforcement. Accordingly, cracks can dramatically impair the aesthetics, durability and serviceability of the structure [1, 2]. The main reason behind plastic shrinkage cracking is considered to be rapid and excessive surface water evaporation in the plastic stage [3-5]. Also, the phenomenon is closely related to settlement, capillary pressure and the duration of dormant period [6].
For conventional concrete, once it is placed in the mould, its solid particles settle under the influence of the gravitational forces, forcing the water in the pore system up to the surface (i.e. bleeding). Consequently, the entire concrete surface is covered with a thin layer of water [7]. However, for self-compacting concrete (SCC) and concrete with low w/c ratio, no free water will accumulate at the surface.
As soon as the evaporation rate exceeds the rate at which water is transported to the surface, the water layer disappears, and water menisci are formed in the pores. This is the onset point of negative pressure (capillary pressure) build-up in the concrete pore system [8]. The progressive evaporation gradually decreases the radius of the menisci resulting in more negative capillary pressure build-up [8]. The capillary pressure in turn causes more settlement by pulling the solid particles down and forcing the pore water to the surface [9]. Gradually due to the consolidation and continues water loss, the solid skeleton of the concrete becomes stiffer and eventually, the settlement stops [6].
At this point, the capillary pressure, applies inward horizontal forces on the solid particles causing the concrete to shrink (i.e. plastic shrinkage). If the concrete is restrained, the plastic shrinkage can lead to tensile strain accumulation at the surface. Eventually, once the tensile strain exceeds the very low early age tensile strain capacity of the concrete, cracks start to form [10].
Many factors can influence the risk of plastic shrinkage cracking such as water-cement ratio (w/c), cement type, member size, admixtures, coarse aggregate content and ambient conditions (i.e. relative humidity, air temperature and wind velocity) [1, 11]. However, despite that many papers are dedicated to study the influence of concrete mixture constituents on plastic shrinkage cracking of SCC, it is still not possible to explain all the cracking incidents based on the current knowledge. It is also not clear why sometimes cracking tendency increases despite of reduction in the evaporation. This is where other parameters such as capillary pressure, internal temperature and/or autogenous shrinkage may offer better explanations.
Although most of the experiments in this study were already performed by other researchers [12, 13], the role of capillary pressure in particular and its relation with evaporation and duration of dormant period have not been discussed. Filling this gap is the objective of this paper. Moreover, the trend of capillary pressure development in the first few hours is especially discussed. The presented research is part of an on-going PhD project at Luleå University of Technology in Sweden which aims at gaining a comprehensive understanding about the mechanism of plastic shrinkage cracking in concrete.

2. Materials and methods

2.1 Materials and mixing process

Tables 1 and 2 show the mix design of the tested SCCs and the composition of the cements. Two reference concert mixtures (Ref.1 with 0.45 w/c ratio and Ref.2 with 0.67 w/c ratio) were produced by Portland limestone cement (CEM II/A-LL 42.5R according to EN 197-1). Fine (0-4 mm and 0-8 mm) and coarse (8-16 mm) aggregates, respectively, constitute 60 and 40% of the total aggregates volume in both Ref.1 and Ref.2. During the experiments, superplasticizer (Sikament 56) with density of 1100 kg/m^3 and 37% by weight of dry content was used. In addition, mineral filler (Limus 40) with density of 2700 kg/m^3 was utilized to stabilize the concrete. The dry material (aggregates, cement and filler) was premixed in a pan type concrete mixer for one minute before the water and superplasticizer (SP) were added. Then the mixing process continued for another 5 minutes. To ensure reproducibility, all the concrete mixtures were produced and tested twice.

Table 1: Mix design of the different tested concretes (W/C = Water-cement ratio, Ref = Reference concrete, CC = Coarse aggregate content, SP = Superplasticizer) in kg/m^3.

Name	**W/C 0.45 (Ref.1)**	**W/C 0.67 (Ref.2)**	**W/C 0.38**	**W/C 0.55**	**Based on Ref.1**		**Based on Ref.2**	
					CC35%	**CC45%**	**SP0.6%**	**SP1.0%**
Cement	380	300	420	340	380	380	300	300
Water	171	200	160	187	171	171	200	200
Agg. 0-4	0	155	0	81	0	0	155	155
Agg. 0-8	998	771	1021	879	1089.4	921.8	771	771
Agg. 8-16	678	628	694	651	586.6	754.2	628	628
Filler	100	220	40	160	100	100	220	220
SP	5.7	2.4	4.6	4.1	5.7	5.7	1.8	3
W/C	0.45	0.67	0.38	0.55	0.45	0.45	0.67	0.67

Table 2: Composition of the utilized cements (produced by Cementa).

Name	**MgO (%)**	**SO_3 (%)**	**Cl^- (%)**	**C_3A (%)**	**Na_2O_{eqv} (%)**	**Density (kg/m^3)**	**Blaine (m^2/kg)**
CEM II/A-LL 42.5R (Bygg)	1.1-1.3	3.3-4.0	0.02-0.04	-	-	3080	430
CEM I 52.5R (SH)	1.1-1.3	3.3-4.0	0.02-0.04	-	-	3125	550
CEM I 42.5N (Anläggning)	1.2-1.5	2.3-2.5	0.01-0.03	1.3-2.7	0.48-0.58	3200	310

2.2 Testing sequence

Four concrete mixtures with different w/c ratios (W/C0.38, W/C0.45, W/C0.55 and W/C0.67) were produced and tested (Table 1). W/C0.45 (Ref.1) was used as a reference for investigating the effect of coarse aggregate content; whereas the effect of SP dosage and cement type was studied by W/C0.67 (Ref.2).

The cement used in Ref.2 (CEM II/A-LL 42.5R) was substituted by two different cements, mentioned in Table 2 in order to study the influence of cement type. To investigate the impact of coarse aggregate content, the ratio in Ref.1 was changed once from 40% to 35% (CC35%)

and once to 45% (CC45%). Moreover, the effect of SP was investigated by changing the dosage from 0.8% of cement weight in Ref.2 to 0.6% in SP0.6% and 1.0% in SP1.0%.

2.3 Method

Ring test setup (NORDTEST-method NT BUILD 433) was developed by Johansen and Dahl at NTNU (1993) [14]. The method is intended to determine the cracking tendency of young concrete (Figure 1). In this method, three identical moulds with two concentric steel rings in each are used. The dimensions of the test setup are presented in Figure 1. Steel ribs (stress raisers) are attached to the concentric rings in order to provide crack initiation points. Each mould is covered by a transparent air funnel with a suction fan. The fan produces 4.5 m/s wind velocity across the specimen surface. During these particular experiments, the room temperature and relative humidity were 20 ± 1˚C and 35 ± 3% respectively. The weight loss (i.e. weight of the evaporated water), capillary pressure and internal temperature were recorded continuously, starting at 60 minutes after the castings up to 18 hours later. One mould was placed on three load-cells (scales) in order to measure the weight of the evaporated water per second. The capillary pressure at 4 cm distance from the surface was measured and recorded in 15 s intervals using two wireless sensors. The internal temperature was recorded in 1 s intervals by using a thermo thread located at 2 cm distance from the bottom of the mould. The concrete surface was visually inspected every 30 minutes in order to determine the time of crack initiation. A digital microscope (to an accuracy of 0.05 mm) and a digital measuring wheel (to an accuracy of ±1 mm) were utilized in order to measure the crack width and the crack length, respectively. After finishing the experiments (19 hours after casting the SCC), the average crack area was calculated, as suggested by Esping and Löfgren [13], according to equation 1:

$$Average \quad crack \quad area = \frac{\sum(crack \quad length \times crack \quad width)}{3} \tag{1}$$

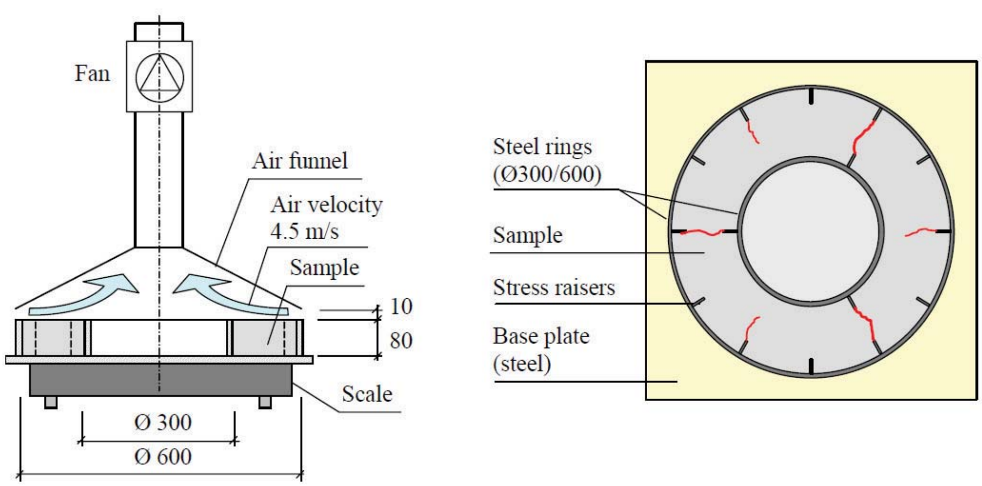

Figure 1: The ring test method setup for plastic shrinkage cracking tendency determination, from [12]. All the dimensions are in mm.

3. Results

3.1 Water-cement ratio

Evaporation: The highest total evaporation was measured in W/C 0.67, followed by W/C 0.55, W/C 0.45 and W/C 0.38 (Figure 2.a). A notable difference was observed between the evaporation of W/C 0.38 and the others. For instance, the total evaporation in its closest neighbour (W/C 0.45) was higher by 37%, while the difference between W/C 0.67 and W/C 0.45 was only 12%. However, W/C 0.38 had the highest initial evaporation rate, followed by W/C 0.45, W/C 0.55 and W/C 0.67, respectively.
Capillary pressure: According to the results, W/C 0.38, W/C 0.45 and W/C 0.55 have almost the same rate of capillary pressure build-up, whereas W/C 0.67 is totally distinguished by its higher rate (Figure 2.b).
Temperature: Increasing the w/c ratios delays the cement hydration and prolongs the dormant period. It should be noted that the temperature was measured at 2 cm distance from the bottom of the mould and thus is not the actual rate of hydration of the concrete. However, it can be considered as an indication of the effect of w/c ratio on the cement hydration.
Average crack area: W/C 0.67 had the highest average crack area, followed by W/C 0.38, W/C 0.55 and W/C 0.45 respectively (Figure 2.d). The average crack area of W/C 0.67 was almost 10 times the average crack area of W/C 0.45.

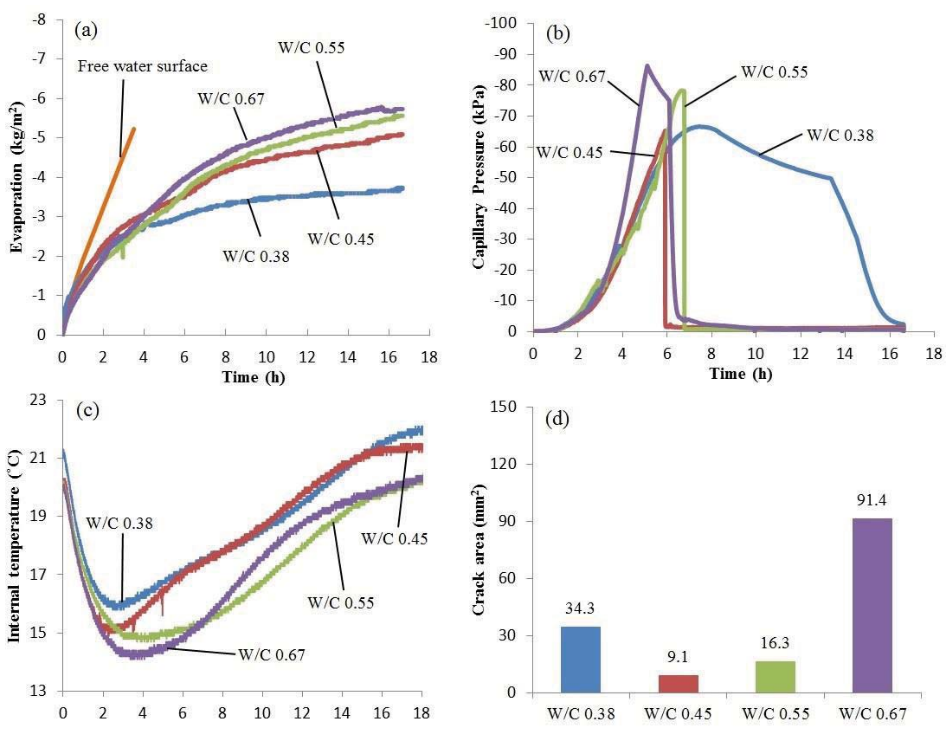

Figure 2: Influence of w/c ratio on (a) evaporation, (b) capillary pressure, (c) internal temperature and (d) average crack area.

3.2 Cement type

Evaporation: Substituting the cement used in "Ref.2" mixture (CEM II/A-LL 42.5R) with CEM I 42.5N led to 31% increase in the total evaporation, while CEM I 52.5R had an opposite impact and reduced it by 14.7% (Figure 3.a).

Capillary pressure: Cement type does not have noticeable influence on the capillary pressure build-up rate, as the slopes of the ascending part of the plotted curves in Figure 3.b are almost identical.

Temperature: The slow hydrating cement of CEM I 42.5N delayed the cement hydration to a large extent and consequently prolonged the dormant period (Figure 3.c). On the other hand CEM I 52.5R accelerated the hydration and shortened the dormant period. This cement was even the only one that reached its heat flow peak before the end of the experiment (after 15 hours).

Average crack area: While CEM I 52.5R and CEM II 42.5R show almost the same cracking tendency (although the former cracked slightly more in comparison), but a notable jump was observed in the cracking tendency of CEM I 42.5N (Figure 3.d).

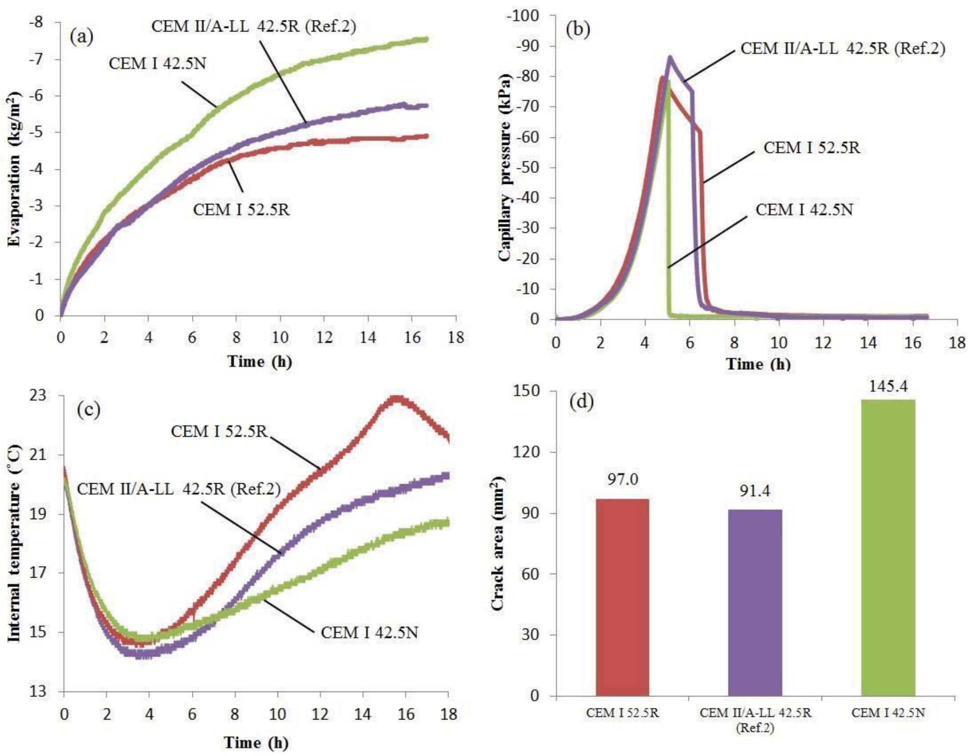

Figure 3: Influence of cement type on (a) evaporation, (b) capillary pressure, (c) internal temperature and (d) average crack area.

3.3 Coarse aggregate content

Evaporation: decreasing the coarse aggregate content from 40% to 35% decreased the total evaporation by 10%. However, the evaporation of CC35% was more than the evaporation of CC40% in the first 5 hours. The concrete was segregated to some extend when the coarse aggregate content was increased to 45%, which in turn led to even more evaporation reduction (Figure 4.a).

Capillary pressure: CC35% had a higher capillary pressure build-up rate, followed by the segregated CC45% and the reference concrete of CC40% respectively (Figure 4.b).
Temperature: Both CC35% and CC45% accelerated the cement hydration in comparison to CC40% (Figure 4.c).
Average crack area: Only 5% reduction in the coarse aggregate content of CC 40% caused an increase in the average crack area of CC 35% by 1036%. Meanwhile, increasing the coarse aggregate content by 5% resulted in 250% increase in the average crack area, which is much lower than the cracking tendency of CC 35% (Figure 4.d).

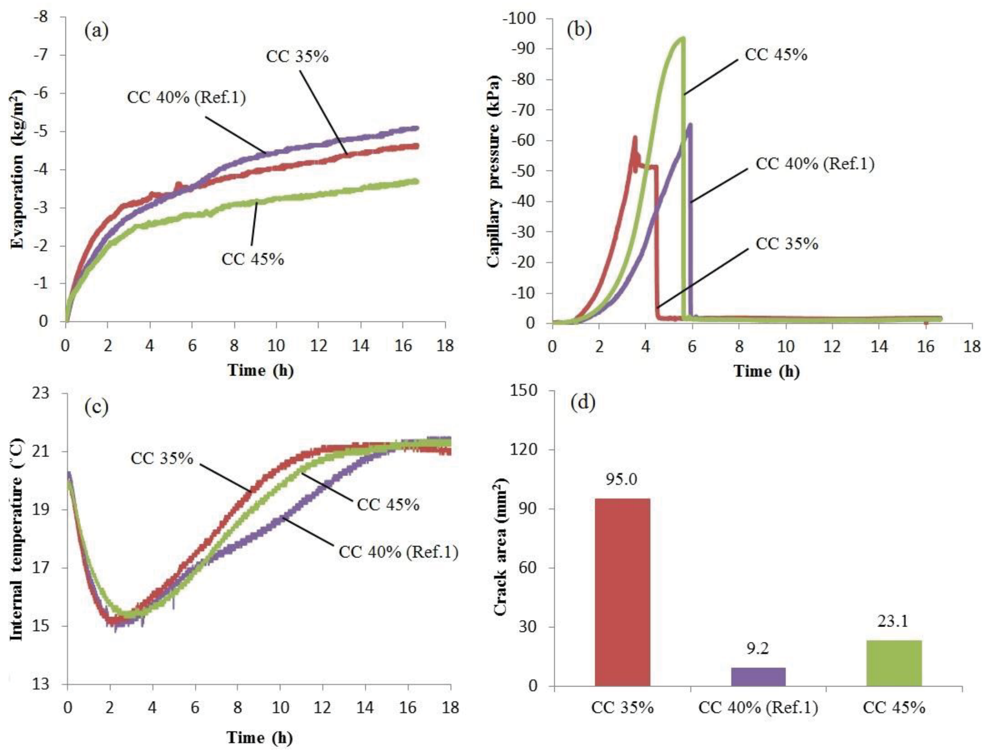

Figure 4: Influence of coarse aggregate content on (a) evaporation, (b) capillary pressure, (c) internal temperature and (d) average crack area.

3.4 Superplasticizer dosage (SP)

Evaporation: Reducing the SP dosage from 0.8% to 0.6% of the cement weight decreased the amount of the evaporated water by 18%. On the other hand the total evaporation was higher by 14% when the SP dosage was increased to 1.0% (Figure 5.a).
Capillary pressure: SP 0.6% led to a faster capillary pressure build-up, while SP1.0% delayed it in comparison to SP0.8% (Figure 5.b).
Temperature: SP0.6% accelerated the cement hydration and shortened the dormant period, while SP1.0% slightly delayed the hydration in comparison to SP0.8% (Figure 5.c).
Average crack area: SP0.6% decreased the average crack area from 91.4 mm^2 in SP0.8% to 56.8 mm^2, whereas this value was increased to 112.4 mm^2 in SP1.0% (Figure 5.d).

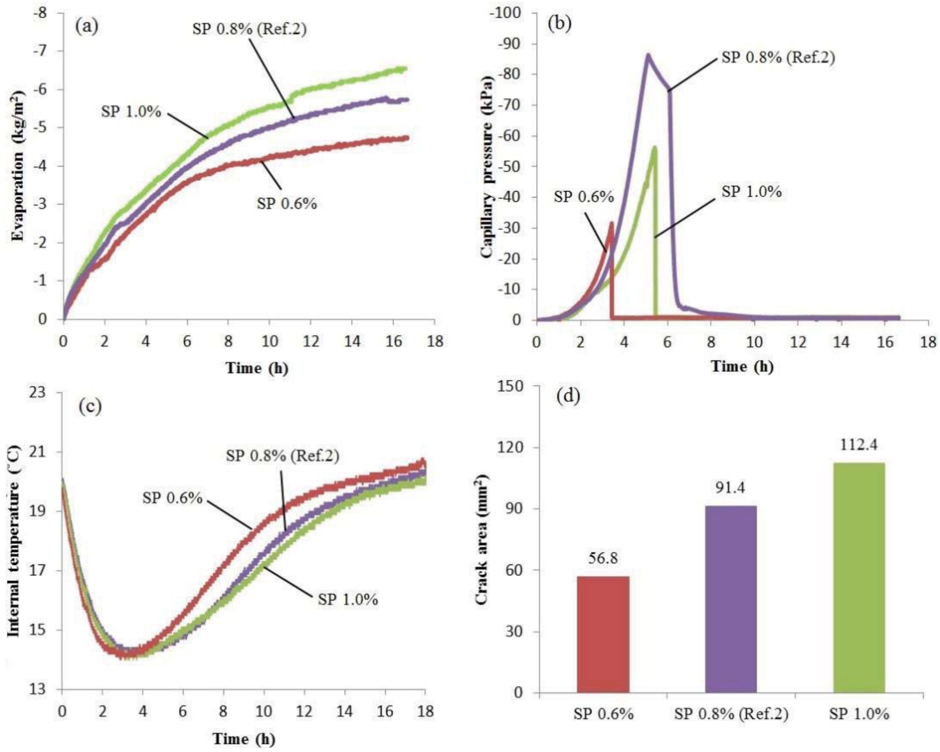

Figure 5: Influence of SP dosage on (a) evaporation, (b) capillary pressure, (c) internal temperature and (d) average crack area.

4. Discussion

Although the maximum capillary pressure value is totally local, the results show that the rate of the negative pressure build-up is almost identical everywhere in the specimen (Figure 6.a and 6.b). During the experiments, both pressure sensors showed equal capillary pressure build-up rate, despite of their different locations. This means that, regardless of the location, the amount of the negative pressure in the pore system is almost identical, especially in the first few hours and before the air-entry point. This phenomenon was also observed in other studies [7, 15].

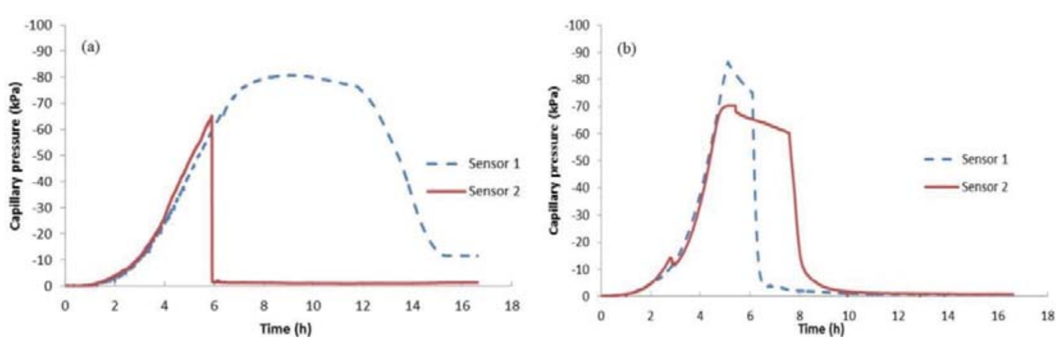

Figure 6: Capillary pressure measured at 4 cm distance from the surface in two different positions, (a) 0.45 w/c ratio and (b) 0.67 w/c ratio.

Since capillary pressure pulls the solid particles together and forces the concrete to shrink, its build-up rate can be considered as an indicator of the amount of horizontal (plastic) shrinkage. Thus, the rate of capillary pressure build-up can also be a governing mechanism of plastic shrinkage cracking alongside evaporation. For example, the concrete with 0.67 w/c ratio has the highest evaporation and crack area (Figure 2.a). It seems that the cracking in this concrete is governed by the evaporation.

However, its slightly higher evaporation (not mentioning its lowest evaporation in the first two hours) cannot justify the huge average crack area difference (Figure 2.d). In this case the higher capillary pressure build-up rate indicates that, at any particular time after capillary pressure build-up onset, W/C 0.67 experiences higher horizontal shrinkage and consequently higher tensile stresses, in comparison to the other tested concretes. Accordingly, in addition to the evaporation, the cracking tendency of concretes with high w/c ratios is amplified by the rate of capillary pressure build-up.

However, the above mentioned cannot explain the cracking behaviour of W/C 0.38. In this case, one reason can be that the concrete experiences higher autogenous shrinkage, since its dormant period is relatively short (Figure 2.c). This hypothesis is backed up with experiments performed by Esping and Löfgren [13]. Meanwhile, the temperature of concretes with high w/c ratios drops faster than those with low ratios. This is probably caused by the higher cooling effect due to the higher evaporation. Moreover, delayed hydration heat development onset (longer dormant period) facilitates more temperature drop.

The main reason behind plastic shrinkage cracking differs based on the early strength gaining class of concrete (rapid or normal). As cement type seems not to affect the capillary pressure build-up rate (Figure 3.b), evaporation, may be the main cause of the cracking (Figure 3.a). It should be noted that the evaporations of the two rapid strength gaining concretes are almost identical, especially in the first 4 hours.

The segregation during CC45% production makes it hard to analyse the results. Thus, the results are not reliable enough for any conclusion to be based on. On the other hand, CC35% had lower evaporation comparing to CC40%. This can be attributed to the higher amount of fines which reduces the pores diameter and consequently decreases the bleeding. The above mentioned can also justify the higher capillary pressure build-up rate. Furthermore, the higher amount of trapped water in the concrete chemically reacts with the cement which means earlier hydration onset and shorter dormant period (Figure 4.c).

In case of the effect of SP dosage, the evaporation seems to be the main crack tendency governing mechanism. However, the relation between the evaporation and capillary pressure build-up rate cannot be fully understood without measuring the settlement and bleeding. On the other hand, SP acts like a retarder as it delays the hydration onset. Hence, at higher SP dosage the retardation will lead to a longer dormant period where water can be lost by evaporation as it's not prevented by the initial structural build-up (Figure 5.c).

5. Conclusion

Based on the results of this study the following remarks can be concluded:

- High capillary pressure build-up rate, only when accompanied with high evaporation, significantly increases the cracking tendency. This can be amplified further by a long dormant period.

- The main driving force behind plastic shrinkage cracking in concretes with high w/c ratio is evaporation alongside high capillary pressure build-up rate and long dormant period. On the other hand, autogenous shrinkage, probably, is the main reason behind crack formation in concretes with low w/c ratio.
- The optimum w/c ratio is between 0.45 and 0.55. Any concrete with w/c ratio out of this range is more prone to early age cracking.
- Reducing the evaporation or compensating the evaporated water in concretes with both low and high w/c ratios (e.g. fogging, curing membrane, wind breaker, etc.) reduces the risk of plastic shrinkage cracking.
- Concretes with normal early strength gaining cements and/or high SP dosage need to be protected against evaporation.

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PAPER IV:

The Relationship between Evaporation, Capillary pressure and Dormant Period during Plastic Shrinkage Cracking of Self-compacting Concrete

Sayahi, F., Emborg, M. and Hedlund, H. (2016), manuscript prepared for submission.

The Relationship between Evaporation, Capillary pressure and Dormant Period during Plastic Shrinkage Cracking of Self-compacting Concrete

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ABSTRACT

Plastic shrinkage cracking, occurring shortly after casting, is believed to happen due to rapid and excessive water evaporation which leads to capillary pressure build-up in the pore system. The negative capillary pressure pulls the solid particles together and forces the concrete to contract, causing the plastic shrinkage. If the shrinkage induced tensile strains exceed the low strain capacity of the young concrete, cracks initially form at the surface and propagate downwards. This paper reports results from experiments performed on self-compacting concrete (SCC) using ring test setups. Influence of concrete mix composition (i.e. water-cement ratio, cement type, coarse aggregate content and superplasticizer dosage) on water evaporation, capillary pressure, rate of hydration heat evolution, time of crack initiation and average crack area has been investigated. It is observed that, a complex correlation between evaporation, capillary pressure build-up rate and duration of dormant period formulates the governing mechanism of the cracking. Moreover, in some cases, the cracking appeared to be also caused by the autogenous shrinkage.

Keywords: Plastic Shrinkage, Cracking, Evaporation, Capillary pressure, Dormant period, Ring test,

1. INTRODUCTION

Early-age shrinkage in concrete may lead to cracking which can dramatically impair the aesthetics, durability and serviceability of a structure [1, 2]. The early-age shrinkage can be divided into: (1) plastic shrinkage due to rapid and excessive evaporation, and (2) autogenous shrinkage due to hydration and chemical reactions [3]. High performance concrete (HPC), ultra-high performance concrete (UHPC) and self-compacting concrete (SCC), are characterised by higher risk of early-age cracking due to their significant shrinkage, rapidly developing after casting.

As the concrete is still in its plastic stage, rapid and excessive water evaporation leads to capillary pressure build-up in the pore system which in turn causes the shrinkage [4-16]. Accordingly, the induced cracks are called plastic shrinkage cracks. This type of cracking, mainly occurring in horizontal concrete elements with large surface to volume ratio (e.g. slabs pavements, industrial floors), accelerates the ingress of aggressive media that might cause damage and durability problem in future, e.g. corrosion of the reinforcement.

Many parameters may affect the risk of plastic shrinkage cracking such as water-cement ratio (w/c), admixture, member size, coarse aggregate content, concrete surface temperature and ambient conditions (i.e. relative humidity, air temperature and wind velocity) [1, 17]. It seems that the phenomenon is also closely related to the duration of the dormant period [23].

For example, research have revealed that usage of shrinkage-reducing admixture (SRA) leads to less water evaporation, reduced settlement, reduced capillary pressure and lower plastic shrinkage cracking tendency [18]. Accelerators appeared to increase the horizontal shrinkage and the cracking; while retarders do the opposite [19, 20]. However, other researchers state that accelerators and retarders decrease and increase the cracking tendency respectively[21]. Other admixtures such as stabilizers (cellulose based) and superabsorbent polymers can also reduce the evaporation rate and cracking tendency of the concrete [3]. It has been also proven that different types of fibres can reduce the width of plastic shrinkage cracks to a large extent [2, 22].

In general, the influence of different parameters on cracking tendency does not necessarily represent their influence on evaporation, capillary pressure or duration of dormant period. In other words, changing a certain mixture constituent may increase the early age cracking tendency of the concrete, while one, two or all three of the above mentioned parameters are reduced and vice versa. The main aim of the present study was to determine relationships between the evaporation rate, capillary pressure and duration of dormant period, influenced by SCC mix design, especially including w/c ratio, cement type , coarse aggregate content and SP dosage.

2. RESEARCH SIGNIFICANCE

Although many papers studied the influence of various concrete mixture constituents on plastic shrinkage cracking of SCC, but still, according to the authors' opinion, it is not possible to explain all the cracking incidents based on the current knowledge. For example, it is not clear why sometimes less evaporation can lead to higher cracking tendency. It seems that parameters other than evaporation, such as capillary pressure and rate of internal temperature development also are crucial. Hence, in this paper, the relationship between the evaporation, capillary pressure and duration of dormant period specially has been addressed

3. MECHANISM OF PLASTIC SHRINKAGE CRACKING

For conventional concrete, immediately after casting, its solid particles settle due to gravity, forcing the water in the pore system to the surface (bleeding). In this case, a thin layer of water covers the entire concrete surface [24, 25]. However, for SCC or concretes with low w/c ratio, although the surface is moist, no free water accumulates at the surface. Evaporation and/or in certain material self-desiccation dry the surface moisture up to a point that the particles at the surface are not covered by water anymore [25]. At this stadium, the evaporation takes place inside the pores which leads to water menisci formation between the solid particles, due to the adhesive forces and surface tension of water. The curvature of these menisci cause negative pressure (capillary pressure) build-up in the concrete pore system, which according to Gauss-Laplace equation (Eq.1), is inversely proportional to the radius of curvature of the meniscus, see also Figure 1[24]:

$$P = -\frac{2\gamma}{R} \cdot \cos\theta = -\frac{2\gamma}{R'} \qquad (1)$$

where P is the capillary pressure in the pore liquid (Pa); R is the radius of curvature of the meniscus in case of full wetting ($\theta = 0$); R' is the radius of curvature of the meniscus for an arbitrary wetting angle ($\theta > 0$); γ is the surface tension of the pore liquid (0.073 N/m for water); θ is the wetting angle, (deg.).

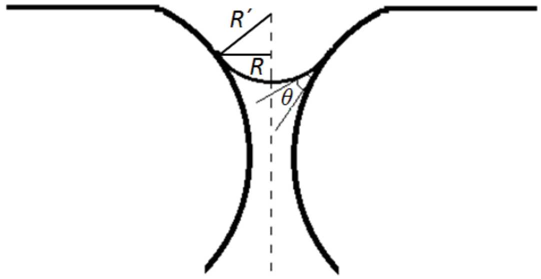

Figure 1, Schematic representation of a water meniscus in an axisymmetric pore perpendicular to the surface.

The progressive evaporation gradually decreases the radius of the menisci which leads to further increase of the negative capillary pressure and solid particles consolidation. The consolidation together with continues water loss due to the progressive capillary pressure build-up reduces the concrete fluidity before the cement hydration starts [17]. Finally, the solid skeleton is stiff enough to resist the gravitational forces, which means that the vertical deformation (settlement) of the concrete either stops completely or continues with a much lower rate.

At this point, the negative capillary pressure is no longer able to compact the concrete and force the pore water to the surface. Instead, it applies inward forces on the solid particles at the concrete surface and horizontal deformation (plastic shrinkage) commences. As a result, the inter-particles distances reduce, causing the concrete to contract. Eventually, the radius of the menisci becomes small enough to reached the so-called "break through" (minimum possible) value and consequently can no longer bridge the pore [15]. This facilitates air penetration in the pore system starting from the largest pores. The capillary pressure suddenly breaks down and the pores are no longer completely filled with water [25].

The empty pores form weak points at the concrete surface which are the origin of strain localization. If the concrete member is restrained (e.g. due to reinforcement, difference in shrinkage of the cross-section, variation in sectional depth, friction of the form, etc.), the shrinkage can lead to tensile strain accumulation, initiating from these empty pores. Once the tensile strain exceeds the very low early age tensile strain capacity of the concrete, cracks start to form initially at the surface and propagating downwards, sometimes through the cross-section if a large external restraint is present.

The process of plastic shrinkage cracking is almost a pure physical process and chemical reactions (i.e. hydration) do not have a decisive role [9, 25, 26, 27]. Thus, the hydration rate or in other words, the length of the dormant period, is important since it can indicate the approximate initial setting time and hydration onset of the concrete. As the initial setting is assumed to be the limit between the plastic and semi-plastic phase of the concrete (see Figure 2), longer dormant period means longer plastic phase and vice versa.

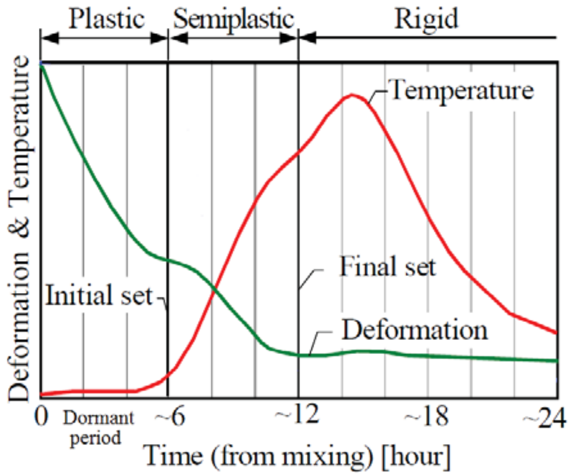

Figure 2, Schematic representation of different phases of concrete based on the early-age deformation and the corresponding heat evolution, based on [21].

4. MATERIALS AND METHODS

4.1 Materials and mixing process

The mix design of the tested concretes and composition of the cements are shown in Tables 1 and 2 respectively. Two reference concretes (Ref.1 with 0.45 w/c ratio and Ref.2 with 0.67 w/c ratio) were produced. Portland cement type CEM II/A-LL 42.5R (Byggcement) containing 6-20 wt% of limestone was used. In both reference concretes 60 wt% of crushed fine aggregates (0-4 mm and 0-8 mm) and 40 wt% of mixed natural/crushed coarse (8-16 mm) aggregates were used. Also, a polycarboxylate ether based SP (Sikament 56) with density of 1100 kg/m^3 and 37 wt% of dry content and mineral filler (Limus 40) with density of 2700 kg/m^3 were used. The slump flow of Ref.1 and Ref.2 were 600 mm and 670 mm, respectively.

All the components were stored at the same temperature at which concrete mixing took place (20±1 ˚C). The aggregates, filler and cement were premixed in a pan type mixer for one minute before the water and SP were added. Then, mixing continued for five more minutes. All the concrete mixtures were produced and tested twice to ensure reproducibility.

Four concrete mixtures with four w/c ratios (W/C 0.38, W/C 0.45, W/C 0.55 and W/C0.67) were tested (according to Table 1). Concrete mix Ref.1 having the w/c ratio of 0.45 was used to study the influence of coarse aggregate content; whereas the effect of cement type and SP dosage was studied on concrete mix Ref.2 having w/c ratio of 0.67. The 40% coarse aggregate content of Ref.1 was reduced to 35% in mix CC35%, in order to study its influence. The effect of SP dosage was investigated by changing its portion from 0.8% of cement weight in Ref.2 to 0.6% and 1.0% of cement weight in SP0.6% and SP1.0% respectively. Moreover, the cement type used in Ref.2 (CEM II/A-L 42.5R) was substituted by two other cements (CEM I 42.5N and CEM I 52.5R), according to Table 2, without changing the mix design.

Table 1, mix design of tested SCCs (W/C = Water-cement ratio, Ref = Reference concrete, CC = Coarse aggregate content, SP = Superplasticizer) in kg/m^3.

Name	W/C 0.38	W/C 0.45 (Ref.1)	W/C 0.55	W/C 0.67 (Ref.2)	SP0.6% (Ref 2)	SP1.0% (Ref 2)	CC35% (Ref 1)
Cement (Table 2)	420	380	340	300	300	300	380
Water	160	171	187	200	200	200	171
Agg. 0-4	0	0	81	155	155	155	0
Agg. 0-8	1021	998	879	771	771	771	1089.4
Agg. 8-16	694	678	651	628	628	628	586.6
Filler (Limus 40)	40	100	160	220	220	220	100
SP (Sikament 56)	4.6	5.7	4.1	2.4	1.8	3	5.7
W/C	0.38	0.45	0.55	0.67	0.67	0.67	0.45

Table 2, composition of the utilized cements (manufactured by Cementa AB, Sweden).

Name	MgO (%)	SO_3 (%)	Cl^- (%)	C_3A (%)	NA_2O (%)	Density (kg/m^3)	Blaine (m^2/kg)
CEM II/A-LL 42.5R (Byggcement)	1.1-1.3	3.3-4.0	0.02-0.04	-	-	3080	430
CEM I 42.5N (Anläggningscement)	1.2-1.5	2.3-2.5	0.01-0.03	1.3-2.7	0.48-0.58	3200	310
CEM I 52.5R (SH-cement)	1.1-1.3	3.3-4.0	0.02-0.04	-	-	3125	550

4.2 Method

The ring test (NORDTEST-method NT BUILD 433) used in this research was developed earlier by Johansen and Dahl at NTNU (1993) [28]. The method is intended to determine the influence of mixture constituents on the cracking potential of fresh concrete at a "macro" level. It consists of three identical moulds with two concentric steel rings in each. The depth of each mould is 80 mm and the diameters of the inner and outer rings are 300 and 600 mm respectively. To provide crack initiation points, steel ribs (stress raisers) are attached to the rings, see Figure 3.

After casting of the concrete between the rings, the mould was covered with a transparent air funnel attached to a suction fan, giving 4.5 m/s wind velocity across the concrete surface. During this particular investigation, the ambient temperature and relative humidity were 20 ± 1˚C and 35 ± 3% respectively. The weight loss (i.e. the evaporation), capillary pressure and internal temperature were recorded continually.

One of the three specimens was placed on three load-cells (scales) in order to measure the water evaporation per second. During these experiments, the capillary pressure was measured at 15 s intervals by means of two wireless capillary pressure sensors filled with degassed water, which were inserted vertically, down to 4 cm distance from the concrete surface right after casting. The internal temperature was recorded in 1 s intervals with a thermo thread located at 2 cm distance from the bottom of the mould. All the measurements start 60 minutes after the castings and were finished 18 hours later.

The concrete surface in all three specimens was visually inspected every 30 minutes in order to determine possible time of crack initiation. The crack width and the crack length were measured by a digital microscope (to an accuracy of 0.05 mm) and a digital measuring wheel (to an accuracy of ±1 mm) respectively. The average crack area is then calculated, as suggested by Esping and Löfgren [21]using equation (2):

$$Average \quad crack \quad area = \frac{\sum(crack \quad length \times crack \quad width)}{3} \tag{2}$$

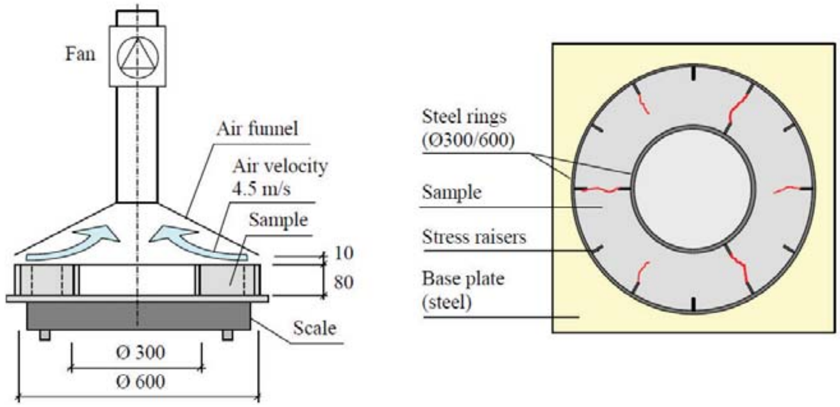

Figure 3, Ring test method setup for plastic shrinkage cracking tendency determination, based on [3] (the dimensions are in mm).

5. RESULTS AND DISCUSSION

Due to the various sizes of the solid particles and their irregular arrangement, the structure of the pore system is not constant. According to Eq.1, the value of capillary pressure depends on the pore radius and thus, it is expected to have different values for each concrete mixture. Even in a certain concrete mixture, the maximum value of capillary pressure is a local event, due to the natural variation of the shape and size of the pores in different locations. However, present results show that, at a given depth, the rate of capillary pressure increase (i.e. slope of the ascending part of capillary pressure-time curve) is almost the same, regardless of the position of the sensors, Figure 4. Moreover, as stated earlier, a higher rate of the capillary pressure build-up means higher tensile forces applied on solid particles in the early stage of hydration. If the higher tensile forces are applied in the plastic stage (i.e. before the initial setting) then the induced shrinkage could be assumed to be pure plastic shrinkage.

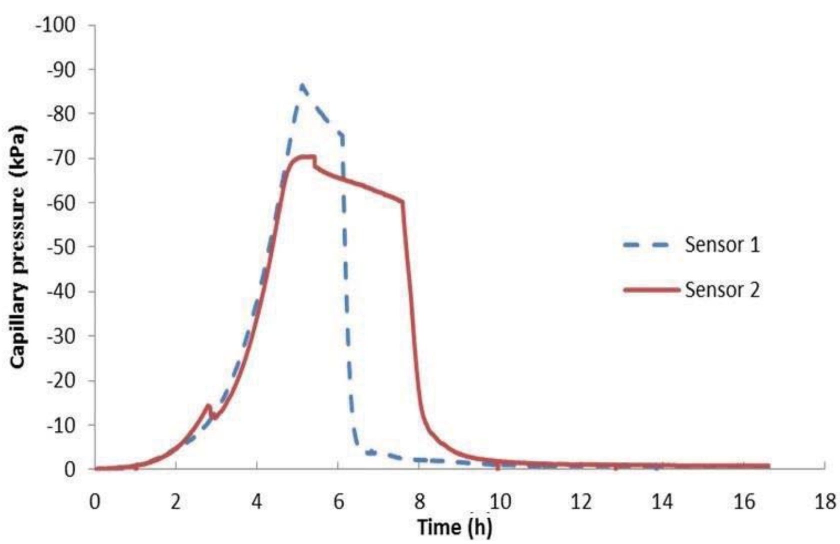

Figure 4, Capillary pressure measured at 4 cm distance from the surface in two different positions, w/c = 0,67 (Ref 2).

5.1 Influence of w/c ratio

The results show that, the total evaporation increases with a higher w/c ratio, Figure 5a. However, the largest average crack area was measured in W/C 0.67, followed by W/C 0.38, W/C 0.55 and W/C 0.45, Figure 5b. Evidently, this obviously does not represent the evaporation trend. Also, the significant difference between the average crack area of W/C 0.67 and the other mixes cannot be explained based on the evaporation solely. Instead, it can possibly be related to the rate of capillary pressure build-up (Figure 5c) and the length of dormant period of each mixture (Figure 5d).

In the concrete with low w/c ratio (W/C 0.38), a lower evaporation means that the radius of the curvature of the menisci in the pores decreases slower, which seems to lead to a somewhat lower rate of capillary pressure build-up (Figure 5c). However, the shorter dormant period (i.e. rapid hydration) (Figure 5d) is an indication of faster stiffening of the concrete skeleton. This implies that the reduction of the menisci radius is no longer compensated by the inward movement of the particles at the pore wall. Instead the reduction of the menisci radius is accelerated which in turn, increases the capillary pressure build-up rate to be almost the same as the other concretes. Moreover, taking the late crack initiation time of W/C 0.38 into account (Figure 5b); it seems that the shrinkage and cracking of SCCs with low w/c ratios is mainly related to the autogenous deformation. This agrees to a large extent with the results of experiments performed by Esping and Löfgren [21].

Furthermore, by increasing the w/c ratio, the cooling effect of the higher evaporation slows down the hydration, i.e. longer dormant period (Figure 5d). The reduction of the capillary pressure build-up rate is then compensated with a higher rate of pore water evaporation (see W/C 0.45 and W/C 0.55 in Figure 5a).

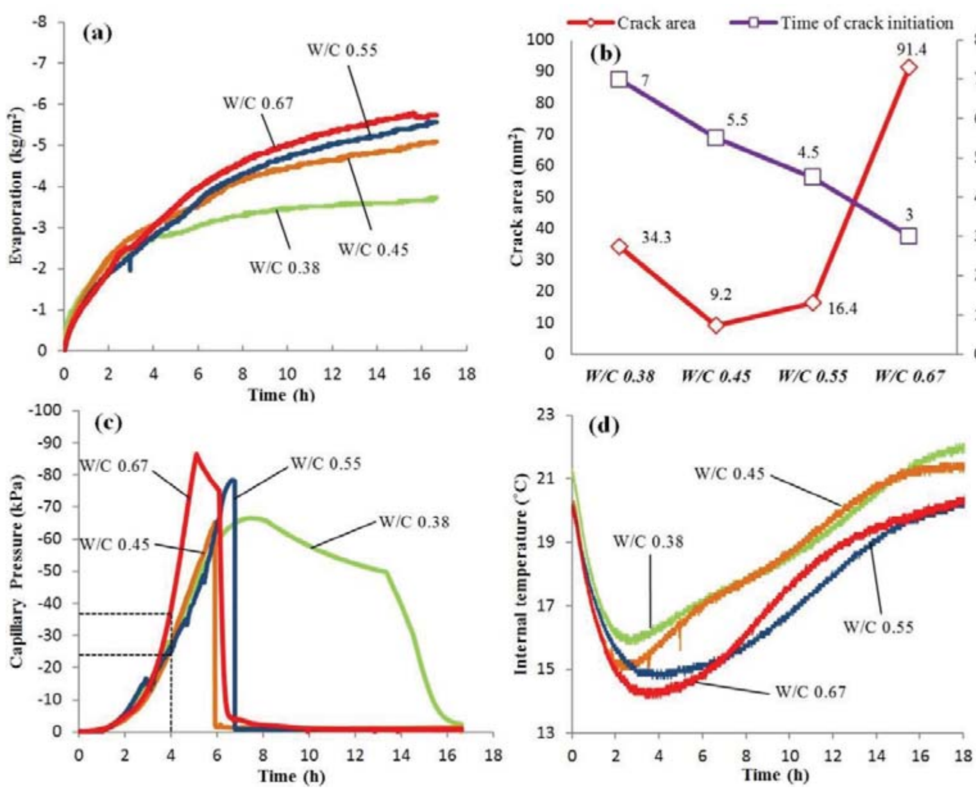

Figure 5, influence of w/c ratio on (a) evaporation, (b) average crack area and time of crack initiation, (c) capillary pressure and (d) internal temperature.

However, in case of a very high w/c ratio, the capillary pressure build-up rate is significantly higher (see W/C 0.67 in Figure 5c). The higher evaporation together with narrower pores due to the presence of higher amount of filler material (Table 1) rapidly decreases the curvature of the water menisci in the pore system and increases the rate of capillary pressure development.

This implies that at any time, the amount of shrinkage that high w/c ratio SCC goes through, is much higher than that which is experienced by SCC with lower w/c ratio. For example, in Figure 5c, the values of capillary pressure of W/C 0.67 and the other three mixtures, at 4 hours after starting the measurement, are compared. As it can be seen, the capillary pressure at this time is -38 kPa for W/C 0.67, while it is around -24 kPa in the other three. This may be interpreted as higher shrinkage in W/C 0.67. It can also be comprehended from photos taken at the end of the experiments, where the cracks in W/C 0.67 is about 10 times wider than those in W/C 0.45 (Figure 6). Since the dormant period is quite long, the shrinkage occurs in the plastic stage, which means that it is a pure plastic shrinkage and the induced cracks are plastic shrinkage cracks.

In general, increasing the w/c ratio accelerates the crack initiation and prolongs the dormant period. Consequently, cracking in SCC with low w/c ratio occurs after the initial setting is reached i.e. in the semi-plastic stage, while SCC with high w/c ratio cracks before the initial setting onset i.e. in the plastic stage. Thus, increasing a low w/c ratio of SCC, converts the early age cracking from being autogenous to pure plastic shrinkage cracking (in high w/c ratio).

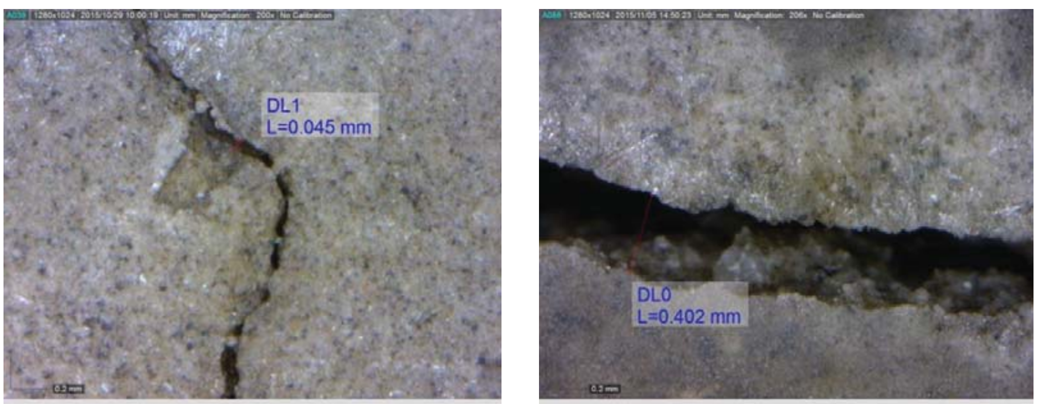

Figure 6, Crack width in (a) W/C 0.45 and (b) W/C 0.67 at 24 hours after casting.

5.2 Influence of cement types

While CEM I 52.5R (SH-cement) reduces the evaporation compared to Ref.2 (produced by CEM II/A-LL 42.5R), CEM I 42.5N (Anläggningscement) leads to a significant increase in the amount of the evaporated water, (see Figure 7a), presumably due to coarser cement particles, enabling easier movement of pore water out to the surface. The slow hardening nature of this cement, delays the setting, which is another reason for higher water drainage. Since changing cement type does not affect the capillary pressure build-up rate (Figure 7c), all the mixtures may develop similar ultimate shrinkage. However, the type of shrinkage will vary. While CEM I 52.5R has a rapid hydration, CEM I 42.5N hydrates in a slower rate (Figure 7d). On the other hand, the cracking occurs after and before the initial setting is reached in the former and latter SCCs, respectively. In other words, cracks in SCC with CEM I 52.5R seems to be mainly autogenous, while the one with CEM I 42.5N experiences plastic shrinkage cracks, which complies well with earlier results of Esping and Löfgren [21].

Hence, it can be comprehended that when the capillary pressure build-up rate is equal, the SCC with the higher evaporation and longer dormant period is the most prone to plastic shrinkage cracking.

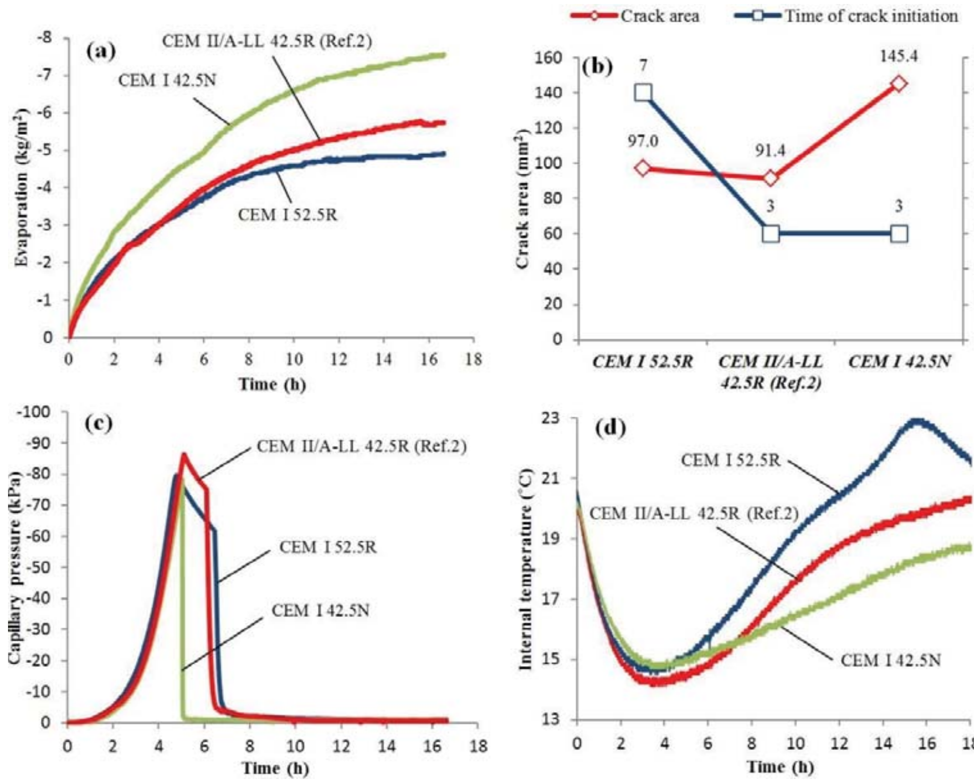

Figure 7, influence of cement type on (a) evaporation, (b) average crack area and time of crack initiation, (c) capillary pressure and (d) internal temperature.

5.3 Influence of coarse aggregate contents

Although decreasing the coarse aggregate content from 40% to 35% decreases the total evaporation, the initial evaporation is increased up to around 5 hours after casting, Figure 8a. The average crack area, on the other hand, increases significantly in comparison to the concrete with higher coarse aggregate content, see Figure 8b. Finer pore structure due to the higher packing, accompanied with higher initial evaporation increases the rate of capillary pressure build-up (Figure 8c).

Since the duration of dormant period is not affected by the coarse aggregate content (Figure 8d), and the crack initiation is accelerated (Figure 8b), reducing the amount of the coarse aggregate in SCC leads to more plastic shrinkage and higher cracking risk. Here, high initial evaporation (in the first 5 hours) is combined with high capillary pressure build-up rate and relatively short dormant period.

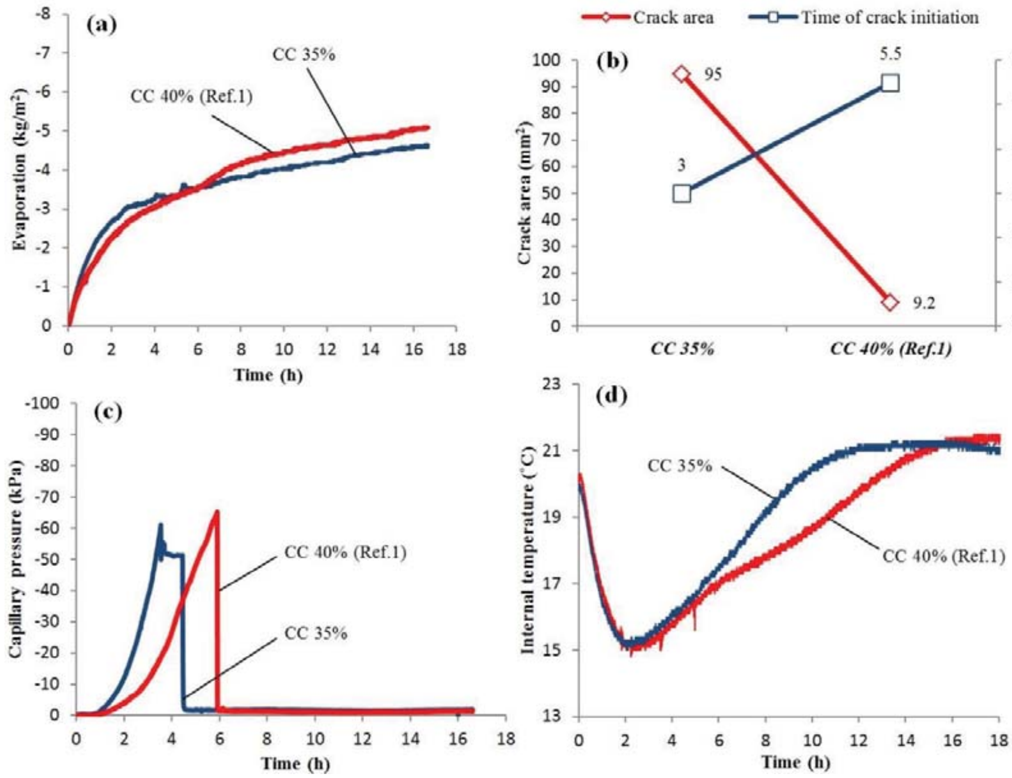

Figure 8, influence of coarse aggregate content on (a) evaporation, (b) average crack area and time of crack initiation, (c) capillary pressure and (d) internal temperature.

5.4 Influence of SP amount

Increasing the SP dosage in Ref.2, increased the evaporation rate, due to the prolonged setting time (Figures 9a and 9d), while reducing it has the opposite effect. The average crack area is increased and decreased for higher and lower the SP dosage, respectively (Figure 9b). The prolonged dormant period in the case of a high SP dosage, facilitates the water transportation to the surface, causing a slower capillary pressure build-up (Figure 9c). Exactly the opposite occurs when the amount of the SP is reduced.

The cracking appeared to be initiated before the initial setting time was reached (see Figures 9b and 9d). The results showed that SP does not affect the type of the early-age crack inducing phenomenon i.e. plastic or autogenous shrinkage. By adjusting the amount of SP in SCC, the concrete will still start to crack in the plastic stage.

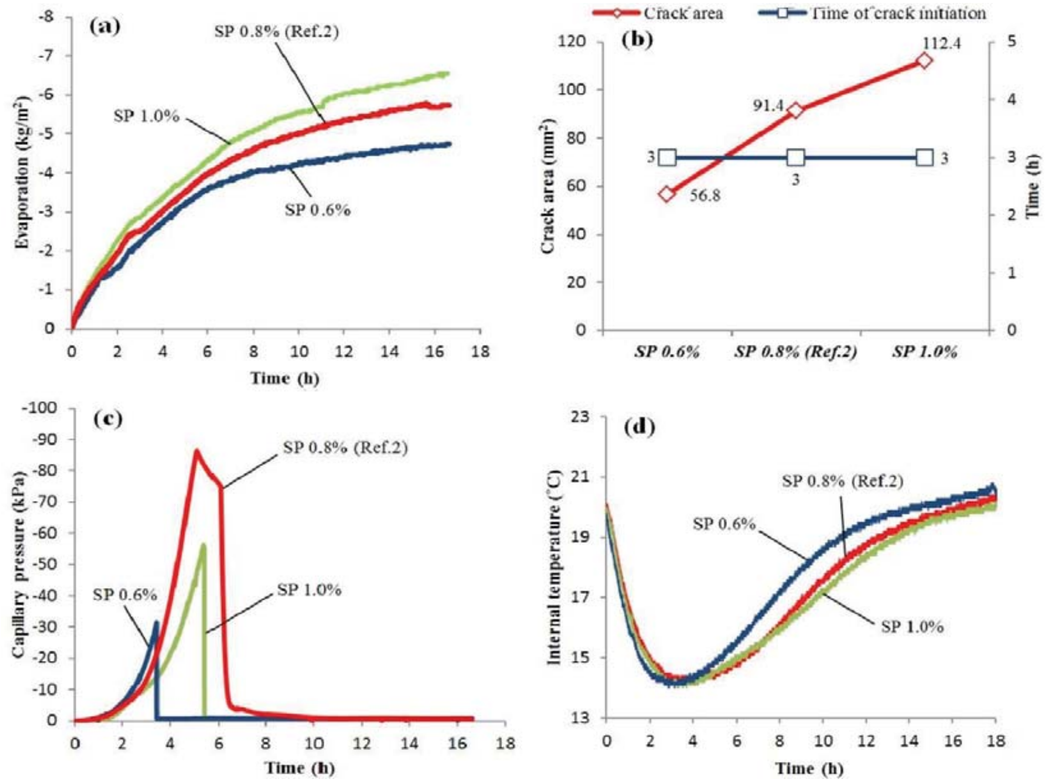

Figure 9, influence of SP dosage on (a) evaporation, (b) average crack area and time of crack initiation, (c) capillary pressure and (d) internal temperature.

5.5 Classification of different combinations

The obtained results can be summarised in Table 3 where cracking risk is related to various combinations of evaporation, capillary pressure build-up rate and duration of dormant period. The classification is made in three classes based on the average crack area, i.e. plastic shrinkage cracking tendency. In this grading, evaporation and capillary pressure build-up rate are subdivided into three levels: i.e. high, moderate and low, based on the value at, or up to five hours after casting. The reason that this period is chosen is that the average of the crack initiation time is around five hours. The range of each level for each parameter is explained in the table.

It should be noted that this table is based on the limited results of this study and thus does not include all the possible combinations. Moreover, the values and ranges in this classification cannot be generalized to all concrete mixtures, as they may differ under different circumstances, e.g. ambient conditions and test setup.

Table 3, cracking tendency classification based on combinations of evaporation, capillary pressure build-up rate and duration of dormant period, in this test series.

	LDP			MDP			SDP		
	HE	**ME**	**LE**	**HE**	**ME**	**LE**	**HE**	**ME**	**LE**
HCPR	3	-	-	-	2 / 3	-	3	-	-
MCPR	3	-	-	-	-	-	-	1 / A	-
LCPR	-	1	-	-	-	-	-	1	A

SDP: Short Dormant Period (< 4 hours)
MDP: Moderate Dormant Period (4-6 hours)
LDP: Long Dormant Period (6 hours <)
LE: Low Evaporation (< 3 kg/m^2)
ME: Moderate Evaporation (3-3.5 kg/m^2)
HE: High Evaporation (3.5 kg/m^2 <)
LCPR: Low Capillary Pressure build-up rate between 3 to 5 hours (< 27 kPa)
MCPR: Moderate Capillary Pressure build-up rate between 3 to 5 hours (27-30 kPa)
HCPR: High Capillary Pressure build-up rate between 3 to 5 hours (30 kPa <)

1: Low cracking tendency (< 30 mm^2)
2: Moderate cracking tendency (30-60 mm^2)
3: High cracking tendency (60 mm^2 <)
A: Autogenous shrinkage cracking
- : No data is available.

6. CONCLUSIONS

Plastic shrinkage cracking is a complex interaction of several variables that may change under different circumstances and conditions at the very early ages. These variables have a direct influence on the evaporation, capillary pressure build-up rate and the duration of dormant period. Based on the results of this study, the following concluding remarks can be listed:

- High capillary pressure build-up rate accompanied by high or moderate evaporation and long, moderate or short dormant period appeared to be the most influential combinations that significantly increase the risk of plastic shrinkage cracking.
- Low capillary pressure build-up rate together with moderate evaporation, regardless of the duration of the dormant period, significantly decreases the plastic shrinkage.
- Increasing the w/c ratio in SCC, converts the early age cracking from autogenous to pure plastic shrinkage cracking.
- Protecting concretes with high w/c ratios against evaporation reduces the risk of plastic shrinkage cracking significantly.
- Cracks in SCC produced using fine rapid hydrating cements are mainly related to autogenous shrinkage, while those containing coarse slow hydrating cements to plastic shrinkage.
- Reducing the amount of the coarse aggregates in SCC accelerates the crack initiation which means that it is more plastic shrinkage governed cracking.
- SP decreases the capillary pressure build-up rate, delays the hydration and increases the evaporation. Concretes with higher SP (Sikament 56) dosage are more prone to plastic shrinkage cracking, despite of the slower capillary pressure development.
- Protecting the concrete with high SP (Sikament 56) dosage against evaporation is an effective way to prevent plastic shrinkage cracking.

7. FUTURE RESEARCH

Based on the results, it is suggested to include both vertical and horizontal deformation measurement in any future research. Investigating the influence of the tested constituents on bleeding can also be an interesting and essential addition as well as changing the ambient conditions. More experiments are needed in order to fill the blank cells in Table 3. Moreover, it is of highly focus to examine the feature of the mixtures in half- and/or full-scale conditions.

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