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Plastic Shrinkage Cracking of Concrete
Part 2: Commentary

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1. Introduction

The purpose of this document is to explain the mechanisms causing the phenomenon of plastic shrinkage cracking (PSC) and also give the rationale for the accompanying guideline for determining the PSC Risk.

The guideline is based on research done at Stellenbosch University and a wide range of literature and publications from as early as 1957 (Lerch 1957). A number of influencing factors causing PSC is taken into account and not just the evaporation rate as proposed by the ACI 305.1-06 recommendation.

Even though the guideline is based on fundamental principles and a large number of tests, a continuous calibration is required as the database of case-studies and tests is enlarged. The reader is invited to send any relevant results and experience with regard to using this guideline to bboshoff@sun.ac.za.

2. The fundamentals of plastic shrinkage cracking

PSC is one of the earliest forms of cracking in concrete and only occurs when concrete is still in the fresh state. Plastic shrinkage is caused by the loss of pore water from the concrete due to evaporation which results in a build-up of negative capillary pressure. Plastic shrinkage is therefore often referred to as capillary shrinkage. Environmental conditions with high evaporation rates increase the magnitude of the plastic shrinkage and are characterised by conditions with a low relative humidity, direct sunlight as well as high wind speeds and air temperatures.

Plastic shrinkage will however not cause cracking unless the shrinkage is restrained. A restraint would result in an imposed strain and if this imposed strain is at any time more than the strain capacity of the concrete, cracking would occur. The strain capacity of concrete reduces significantly when the concrete stiffens, i.e. around the initial setting time. This phenomenon is shown in Figure 1 and is based on test results found in literature (Branch et al. 2002, Swaddiwudhipong et al. 2003, Holt and Leivo 2004, Hannant et al. 1999, Dao et al. 2009, Kim et al. 2002). Two examples of induced strain are also shown and it is clear that a high plastic shrinkage would result in cracking. The cracking typically initiates at around the initial setting time of the concrete.

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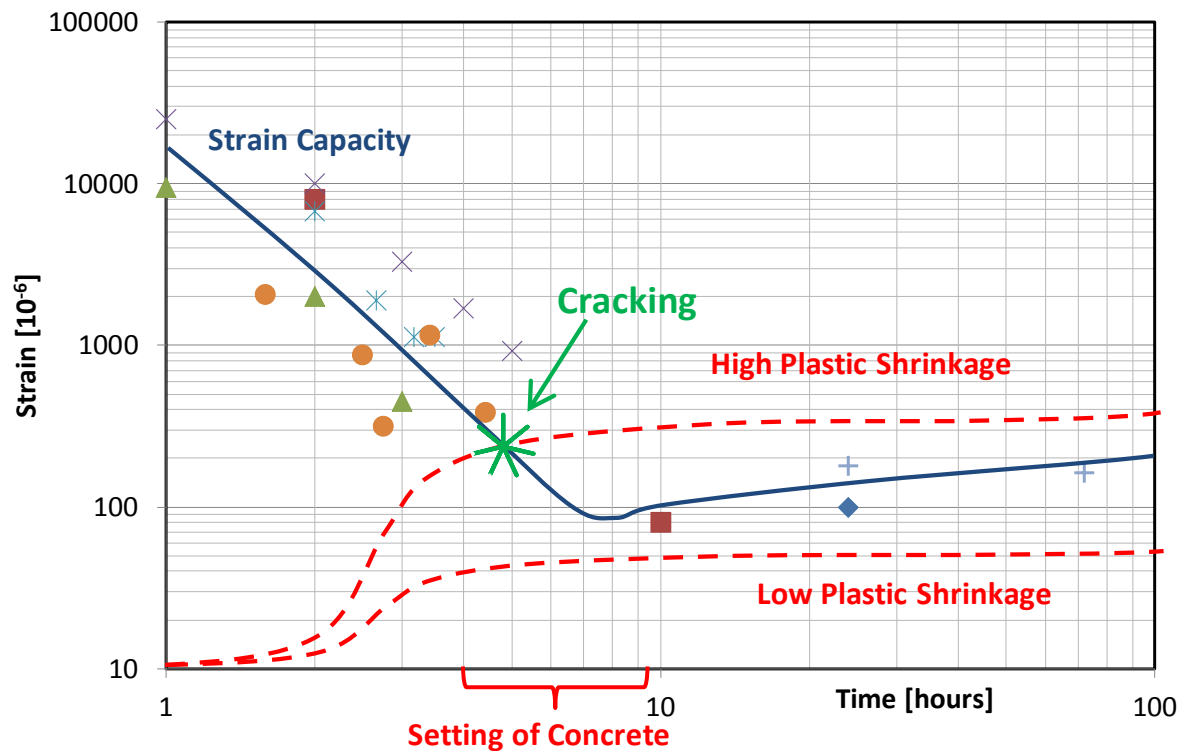Telephone: +27-(0)21-8084498 ⬧ Fax: +27-(0)21-8084947

Figure 1. The typical strain capacity of concrete with a schematic representation of induced plastic shrinkage (Branch et al. 2002, Swaddiwudhipong et al. 2003, Holt and Leivo 2004, Hannant et al. 1999, Dao et al. 2009, Kim et al. 2002)

In order to determine when PSC is likely to occur, the factors influencing the rate and magnitude of plastic shrinkage need to be understood. Plastic shrinkage is however a complex phenomenon which is influenced by a number of interdependent mechanisms/properties which include:

- The rate and volume of bleeding
- The rate of hydration and setting time
- The evaporation rate of the environment
- The concrete temperature
- The size and distribution of fine particles
- The admixtures used

The size and distribution of the fine particles typically only influence the bleeding while the admixtures typically influence the bleeding and setting time. In addition, the concrete temperature mainly influences the evaporation rate and setting time. The list can thus be reduced to bleeding, setting time and evaporation rate. These three properties can also be easily measured.

As mentioned, PSC can only occur if the volume change is restrained and there is typically always some type of restraint in a concrete member, e.g.:
- Reinforcing steel
- Change of sectional dimensions
- The surface of the formwork

There are thus a large number of different factors influencing PSC and controlling the evaporation rate is not always sufficient for controlling PSC.

The model proposed in this document calculates the risk of PSC and is based on the four most prominent factors influencing PSC, namely the bleeding, setting time, evaporation rate and the volume of micro fibres added. Even though this is a simplification of the actual mechanisms causing the cracking, it has been shown to predict the cracking intensity with relative accuracy (Boshoff et al. 2012). In this model the strain capacity is however assumed to be the same for all types of concrete, but this assumption is sufficient for the purpose of this model.

The addition of fibres reduces the risk of PSC due to a resulting increase in strain capacity. As this model does not include the strain capacity directly, the effect of the fibres is included empirically based on a large number of laboratory tests.

The model for calculating the risk of PSC is based on the following four properties and each are explained in the following sections:
1. Plastic Period
2. Bleeding Volume
3. Evaporation Rate
4. Synthetic micro fibres.

3. Plastic Period

The Plastic Period of concrete is, for the purpose of this model, defined as the period after the compaction of the concrete to the initial setting time (point of stiffening) of the concrete. During this time the bulk of the plastic shrinkage occurs.

It has been shown that the volume of water evaporating from the concrete before the setting of the concrete is linearly related to the magnitude of plastic shrinkage (Radocea 1994). The duration of the Plastic Period can be used together with the Evaporation Rate (Section 4) to determine the total volume of water that evaporated. This can, in turn, be related to the magnitude of plastic shrinkage.

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The evaporation that occurs before the concrete is placed and vibrated will not result in any plastic shrinkage and only once the concrete is compacted will the water evaporation have an influence. The Plastic Period is therefore defined as the time from compaction to the initial setting time. This is often unpredictable as this period is typically dependent on the waiting time at the construction site and traffic conditions if ready-mix trucks are used to transport the concrete. It would be sufficient to estimate the plastic period for both the typical case and the worst case scenario. Note that the worst case scenario is when the Plastic Period is the longest.

The initial setting time of concrete is dependent on a large number of factors, including the setting time of the cement, concrete temperature, organic content of the aggregates and admixtures used. It is therefore suggested that the initial setting time is measured for each concrete application. However, with sufficient experience with specific materials and conditions this can be estimated without testing.

It is important that the test simulates the concrete temperature of the on-site conditions as it would significantly influence the setting time. A higher temperature would result in an earlier setting time. Hot water can be used as mixing water to increase the concrete temperature.

There are a number of tests that can be used for determining the setting time. The following three tests are proposed:

1. Using a concrete mortar penetrometer according to ASTM C 403. If done in a laboratory the concrete temperature and ambient temperature should be representative of the expected temperatures on-site.
2. Using the test for the setting time of cement according to SANS 50196-3, but sieving the fresh concrete through a 4.75 mm sieve to obtain a mortar. If done in a laboratory the concrete temperature and ambient temperature should be representative of the expected temperatures on-site.
3. Pencil test. A simplified test which can be used with some degree of accuracy is indenting the concrete surface with the sharp end of a pencil. If the pencil does not penetrate the concrete to leave a pronounced indentation on the surface when pressed lightly, the concrete has reached initial set. Evaporation of the sample should be prevented during this test. A glass or Perspex cover over a ¾ filled cube would be sufficient.

Typical values for the Plastic Period (measured in hours) are shown in Table 1. Note these values will be further calibrated when the database of case-studies is increased.

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Table 1. Typical values of the Plastic Period

	Plastic Period [hours]
Fast Setting Concrete	1 to 2
Medium Setting Concrete	2 to 3
Slow Setting Concrete	3 +

4. Evaporation Rate

The calculation or measuring of the evaporation rate is the next important step for calculating the PSC Risk. When the length of the Plastic Period is known, this could be used together with the evaporation rate to determine the volume of water lost during this time. As mentioned before, the volume loss is directly related to the magnitude of plastic shrinkage. The Bleeding Volume does however offset the evaporation to some extent.

Models for predicting the evaporation rate of free concrete water are available (e.g. Uno 1998) and these models are all based on the following parameters:
- The wind speed
- The relative humidity
- The ambient temperature
- The concrete surface temperature

The evaporation rate could also be measured directly by weighing a cast sample continuously on site. However, this is typically not required as these models adequately predict the evaporation rate (Uno 1998). The two models proposed in the accompanying document are based on the work by ACI Committee 305 (Figure 2) and Uno (1997), i.e:

$$ER = 5\left[(T_C + 18)^{2.5} - \frac{RH}{100}(T_A + 18)^{2.5}\right](V + 4) \times 10^{-6} \tag{1}$$

with ER the evaporation rate, T_c the concrete temperature, T_a the ambient temperature, RH the relative humidity in % and V the wind speed in km/h.

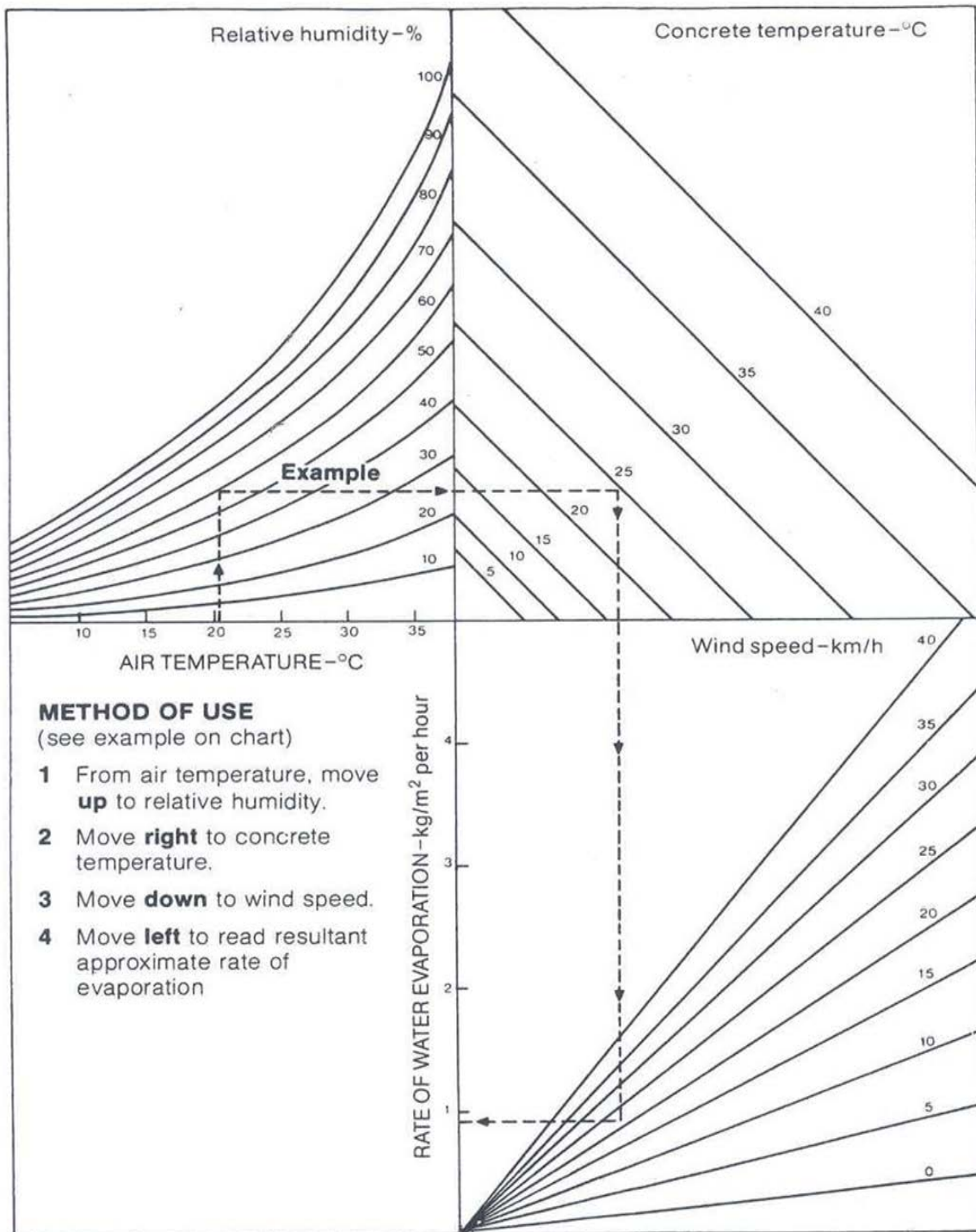Typical values of the Evaporation Rate is show in Table 2.

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Figure 2. Nomograph to determine the evaporation rate of concrete surface water.

Table 2. Typical values of the Evaporation Rate

	Evaporation Rate [kg/m^2/h]
Low Evaporation	0 to 0.5
Medium Evaporation	0.5 to 1.0
High Evaporation	1.0 +

5. Bleeding Volume.

Bleeding is the process of free water moving upward in concrete as the particles settle due to gravitation. The settlement will continue until the concrete starts to stiffen or when the particles become mechanically interlocked and can therefore settle no further. Settlement normally ceases due to the stiffening, therefore bleeding typically stops when concrete has reached the initial setting time. The phenomenon of bleeding is probably the single most important reason why the risk of plastic shrinkage cracking cannot be related to only the evaporation rate.

The bleeding is quantified in this model as the total volume measured in kg/m^2. This should not be confused with the rate of bleeding which is measured in kg/m^2/hour. Note that the Bleeding Volume is to some extent dependent on the duration of the Plastic Period, as explained above.

The Bleeding Volume can be measured on-site or in a laboratory. A small container with a dimension/diameter of between 100 mm and 150 mm and a depth around 20 mm more than the specific concrete member to be cast would be sufficient. The sample should be filled and compacted to the same depth as the specific concrete member.

The specimen should be weighed directly after compaction using a scale accurate to the nearest gram. A lid should be placed firmly on the container to prevent evaporation and left undisturbed until the concrete reaches the initial setting time.

After the initial set of the concrete, the water should be removed from the surface by tilting the specimen slightly and extracting the water with a syringe. The specimen without bleed water should then be weighed once again. The Bleeding Volume can then be calculated using the following equation:

$$Bleeding\ Volume = \frac{m_{start} - m_{final}}{A} \tag{2}$$

with m_{start} the mass in kg just after compaction, m_{final} the mass in kg after the bleed water was removed and A the surface area of the specimen in m^2.

The bleeding behaviour is dependent on a large number of aspects, including:
- Water content of the concrete
- Aggregate particle size and distribution
- Powder/fine content
- Cement and extender types and volumes
- The setting time of the concrete
- The volume of fibres added
- The depth of the concrete member

Typical Bleeding Volumes are shown in Table 3. With experience these values could however be estimated without testing.

Table 3. Typical Bleeding Volumes

	Bleeding Volume [kg/m^2]
Low Bleeding	0 to 0.75
Medium Bleeding	0.75 to 1.5
High Bleeding	1.5 to 3.0

6. Plastic Shrinkage Cracking Risk

The Plastic Shrinkage Cracking Risk (PSC Risk) can be estimated with the following equation using the values calculated in the previous sections. Note the Fibre Risk Reduction is explained in the following section.

$$PSC\ Risk = (Plastic\ Period\ \times Evaporation\ Rate) - Bleeding\ Volume - Fibre\ Risk\ Reduction$$

(3)

This relation was verified using a large number of tests all done at Stellenbosch University (Combrinck 2011 and Maritz 2012). This relation is based on the following fundamental principles:
- There is a linear relationship between the plastic shrinkage and the volume of water evaporated from the concrete till the initial setting time of the concrete.
- The evaporation of bleed water does not cause any plastic shrinkage.
- The plastic shrinkage cracking severity is directly related to the magnitude of plastic shrinkage.

The tests used to determine this relation was done over a period of 3 years and different concrete mix designs, evaporation rates, temperatures and additives were used. These variations resulted in a range of bleeding volumes, setting times and evaporation rates, shown in Figures 6 and 7.

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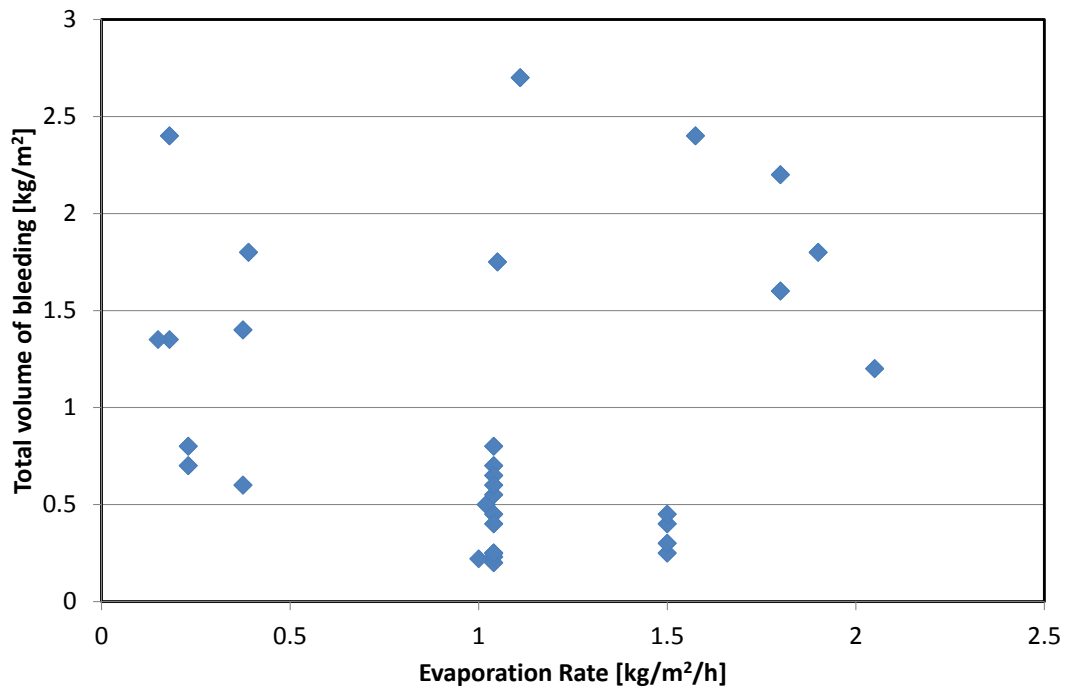STRUCTURAL
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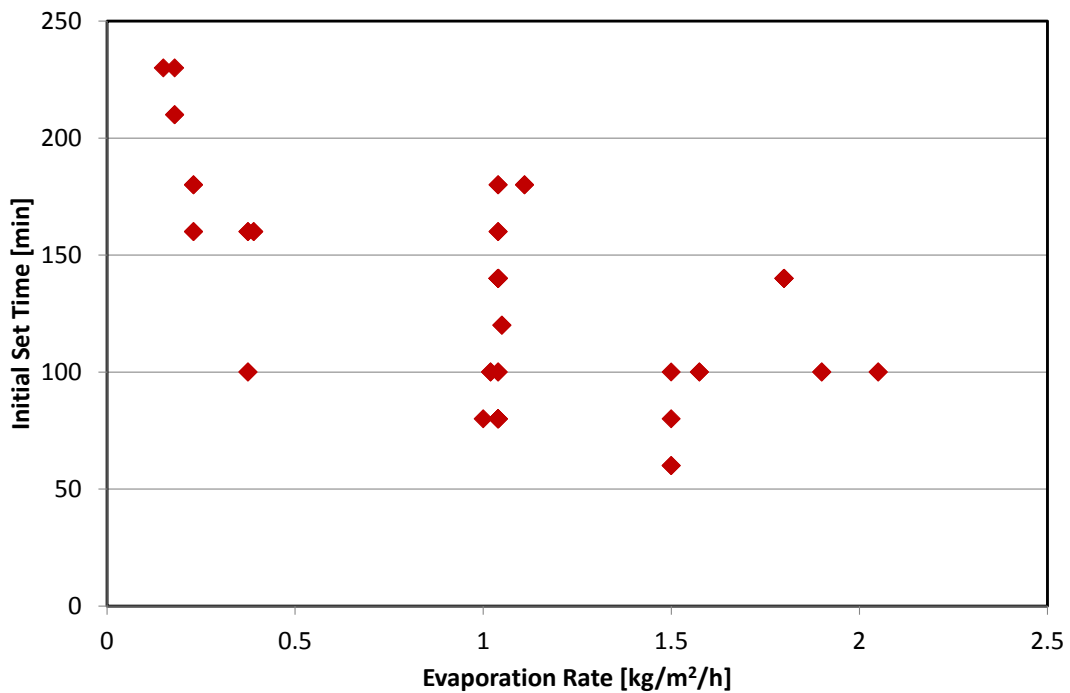Figure 6. The different volumes of bleeding measured for the tests against the evaporation rate.

Figure 7. The different initial setting times for the tests against the evaporation rate.

The total bleeding volume ranged from 0.2 kg/m^2 to 2.7 kg/m^2 and is deemed sufficient to represent different typical concrete mixes. It is however acknowledged that even though an adequate distribution of initial setting times were used, no concrete mix had an effective Plastic Period of more than 4 hours. Such a delayed setting is in most practical applications not ideal.

All the results are shown in Figure 8. A relative narrow band is evident correlating the plastic shrinkage crack widths to the PSC Risk as calculated in Equation 3. This indicates that the PSC Risk model is an effective way of expressing the severity of plastic shrinkage cracking. It is important to note that even at a PSC Risk of 0 kg/m^2 there are still some cracking evident. This is due to some interaction between plastic settlement cracking and PSC. It is however believed that this does not influence the validity of this model.
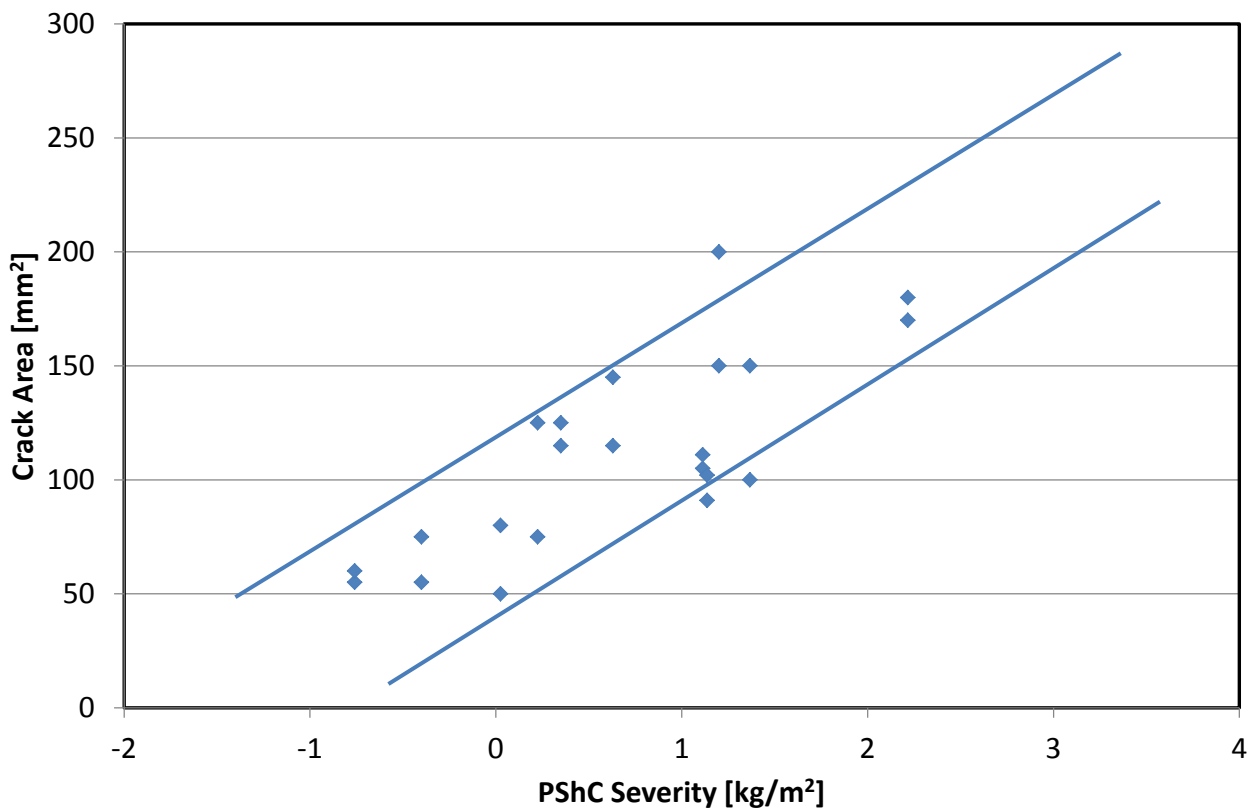

Figure 8. The PShC Risk shown against the measured crack area.

Typical PSC Risk values are categorised in Table 4 and can be used to evaluate the estimated PSC Risk. The PSC Risk values are not related to crack area as shown in Figure 8 as the crack area would vary for different restraints found in each specific application. Therefore no accurate prediction of the plastic shrinkage crack area can be made using this model. It does however still give a good indication of the risk of PSC.

Table 4. Categories for PSC Risk values

	PSC Risk [kg/m^2]
No Risk	< 0.0
Low Risk	0.0 to 1.0
Medium Risk	1.0 to 2.0
High Risk	2.0 to 3.0

This model assumes a thickness of 150 mm of the concrete member. A smaller thickness would result in a slight increase of the PSC Risk value and vice versa. This is however currently under investigation and will be included in this model in the near future.

The PSC Risk can be reduced by the following:
- Reducing the duration of the Plastic Period
- Increasing the Bleeding Volume
- Reducing the Evaporation Rate
- The addition of synthetic micro fibres

Note that increasing the Bleeding Volume would in most cases negatively influence the concrete surface quality. The evaporation rate can be effectively reduced by a number of curing methods on site. It is however important to apply these curing methods during the Plastic Period otherwise the PSC Risk will not be reduced.

The effect of synthetic micro fibres on the PSC Risk is explained in the following section.

7. Reducing PSC Risk using synthetic micro fibres.

It has been shown by many authors (e.g. Branch et al. 2002, Wongtanakitcharoen 2005) and also confirmed by tests done at Stellenbosch University that the addition of micro fibres indeed reduces PSC. The addition of fibres increases the strain capacity of the fresh concrete, hence reducing the risk of PSC. The effect of using different volumes of fibres on the calculated PSC Risk value is shown in Figure 9. The show results is a small set of results and the reader is referred to (Combrinck 2011, Maritz 2012) for a more detail description of all PSC test results which included fibres.
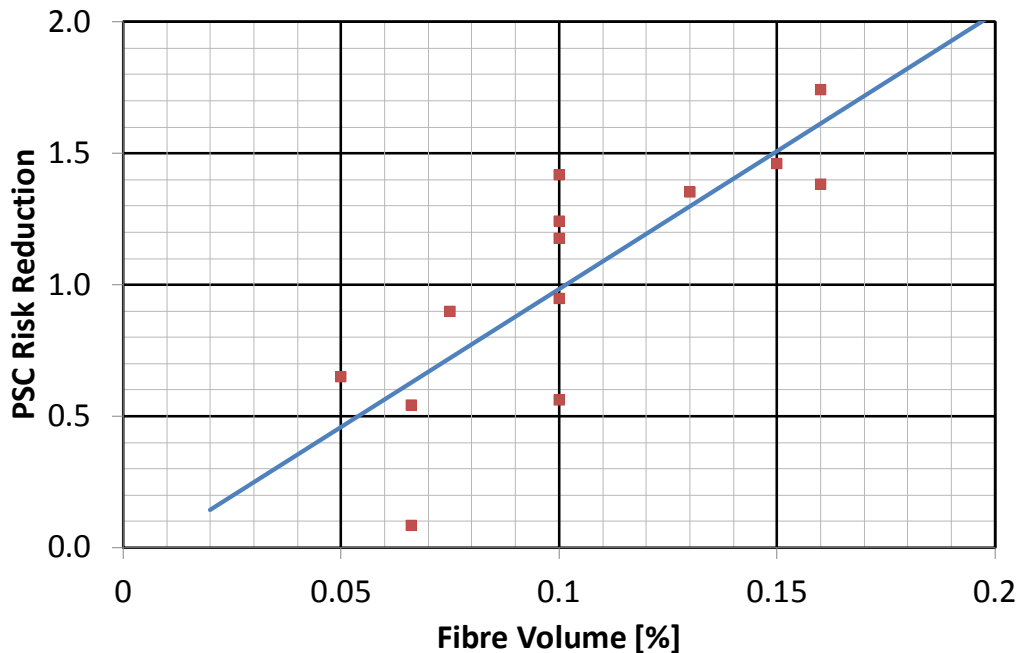
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Figure 9. The expected PSC Risk reduction at different fibre volumes.

The types of fibres tested were:
- Polypropylene: diameter of 35 μm and length of 12 mm
- Polyester: diameter of 20 μm and length of 12 mm

It was found that the effectiveness of the two fibre types listed is similar at the same volume dosage. When fibres with different properties than those mentioned are used the PSC Risk reduction will probably be different to the values shown in Figure 9 and should be tested to determine their effectiveness.

It is important to note that the values shown in Figure 9 are expressed in terms of the volume of fibres added. Due to different densities, different types of fibre will relate to a different mass for a given volume. Polypropylene has a relative density of 0.91 and polyester a relative density of 1.3.

The PSC Risk Reduction determined using Figure 9 can be used to reduce the PSC Risk as it is included in Equation (3). Note that it is important that conventional curing methods should still be implemented when fibres are added.

8. Concluding Summary

This document serves as a commentary document to the accompanying document outlining a guideline for determining the risk of plastic shrinkage cracking for a specific application. The mechanisms of plastic shrinkage cracking are explained in detail.

It is further shown that the risk of plastic shrinkage cracking is based on four aspects, namely the total volume of bleeding, the rate of water evaporation, the duration of the plastic period and the volume of micro fibres added.

This guideline can be used to determine the risk of plastic shrinkage cracking, called the PSC Risk, and also determine how different mitigation methods, including the addition of fibres, would reduce the calculated risk.

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