



# Calculation of Actual Concrete Shrinkage Magnitude



By:

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## 1.0 INTRODUCTION

Most often, the quantification of shrinkage strains and magnitude are not necessary requirements, as provision of adequate number and spacing of shrinkage and construction joints normally would ensure a trouble free concrete slab construction.

It is only when troubles arise like serious cracking and curling is there a need to look into actual magnitudes particularly if liability or litigation threats are in the offing. The actual magnitude of shrinkage strains are quantifiable based on well established procedures published by the American Concrete Institute (ACI 209R-92).<sup>1)</sup> Particularly, this calculations would be needed in order to determine whether a member would crack or not due to shrinkage or if the problem of cracking is due to some other causes. In such cases, it is necessary that the actual magnitude of shrinkage strains be determined to ensure that these strains do not exceed the permissible limits.

### 1.1 Prediction of Actual Shrinkage Values based on ACI 209R-92

Concrete shrinks due to moisture loss. However, the actual magnitude of ultimate shrinkage is dependent on a lot of factors as contained in ACI 209R-92.

These factors are:

- Relative Humidity
- Minimum Thickness
- Water Cement Ratio W/C
- Slump
- Air Content
- Fines Content

In order to predict the actual shrinkage, it is necessary to perform actual calculations taking into account the foregoing factors.

Totally neglecting these procedures renders any conclusion invalid and at best highly speculative.

The use of a real construction problem would best illustrate the need for and importance of Calculation procedures based on universally accepted “*State of Practice*”.

This was what happened in a real world project of ours,<sup>2)</sup> where major Shrinkage cracking has occurred; blame is being placed squarely on the *Engineer of Record* with various claims that are unsubstantiated. One of these is a claim by the contractor’s hired foreign consultant that shrinkage stresses even with the high W/C ratio is not the cause of cracking. The consultant even provided *oversimplified calculations* just to justify that cracks were not due to shrinkage since by not being able to do so, the very high and non compliant W/C ratio as placed will surely point to the main reason for the cracking.

In order to disprove the self serving and highly erroneous calculations presented, we proceeded with the appropriate Calculation based on a rational procedure as recommended in ACI Committee 29<sup>1)</sup>.

**This is the main topic of this article and by outlining the procedures taken, the reader/s will be guided in how actual shrinkage is calculated which even if complicated is required particularly when the problem blows into a litigation headache.**

<sup>1)</sup> ACI Committee 209. “*Prediction of Creep, Shrinkage and Temperature Effects in Concrete Structures*”. ACI 209F-92 contained in ACI Manual of Concrete Practice, 1996, Part 1.

<sup>2)</sup> For Obvious Reasons the Project and personages involved cannot be named.

### 1.1.1 Calculation of the Ultimate Shrinkage Value

The ultimate shrinkage value  $\epsilon_{SH\infty}$  can be predicted for conditions other than standard<sup>31</sup> using:

$$\epsilon_{SH} = \epsilon_{SH\infty} \times K_H^s \times K_D^s \times K_s^s \times K_F^s \times K_B^s \times K_{AC}^s$$

Where:

- $\epsilon_{SH}$  = is the strain at standard or other conditions
- $\epsilon_{SH\infty}$  = Ultimate Strain
- $K_H^s$  = Correction Factor for Relative Humidity
- $K_D^s$  = Correction Factor for Minimum Member Thickness
- $K_s^s$  = Correction Factor for Concrete Consistency
- $K_F^s$  = Correction Factor for Fine Aggregate Content
- $K_B^s$  = Correction Factor for Cement Content
- $K_{AC}^s$  = Correction Factor for Air Content

The attached charts in **Appendix "B"** give the corresponding values used on our calculations for the various conditions based on **ACI 209R-92**.

Based on the foregoing equation and quantification of actual conditions for the specific project (see **Appendix "A"** for a complete detail of the above.)

The following values for the correction factors for ambient Project conditions have been used.

Factor	Actual Condition at Time of Pour A]	Shrinkage Correction Factor
Ambient Relative Humidity	85%	$K_H^s = 0.48$
Minimum Thickness	100mm	$K_D^s = 1.0642$
Cement Content	285 kg/cu.m.	$K_B^s = 0.81099$
Slump	2 inches	$K_s^s = 0.97$
Air Content	2%	$K_{AC}^s = 0.97$
Fines Content	50%	$K_F^s = 1.0$
Product		0.3654

A] Assumed Values applied to both conditions uniformly.

The foregoing values need to be applied on the Ultimate Shrinkage Value  $\epsilon_{SH\infty}$  to yield the shrinkage strains at actual conditions.

It is not correct to use assumed "Standard Values" as was done by the contractor's Foreign Consultant for the concrete in question because the conditions were not standard for this project.

In addition, the concrete as poured by the contractor excessively violates the specified maximum Water Cement Ratio W/C (**Specified 0.42 vs. Actual 0.8333**) by **98.4%** based on tests of Water Content and Water Cement Ratio W/C conducted by a New Zealand Laboratory and as cited in the contractor's Consultant Final Report.

However, the effect on the resulting strains is non linear and is greater at higher water contents.

The **Portland Cement Association**<sup>41</sup> has a widely accepted and well documented procedure for prediction of what shrinkage strains could be under various Water Cement Ratios and under other equally important considerations for the ambient project conditions existing during the pour. (thus, it is important for the consultant and the PM to record these conditions at every pour).

The chart below is taken from Reference 2.0 and shows how the shrinkage contribution from various Water Cement Ratios could be quantified:

From: Ref. 2.0 *PCA Handbook Design of Concrete Mixtures, 13<sup>th</sup> Ed. Page 155.*

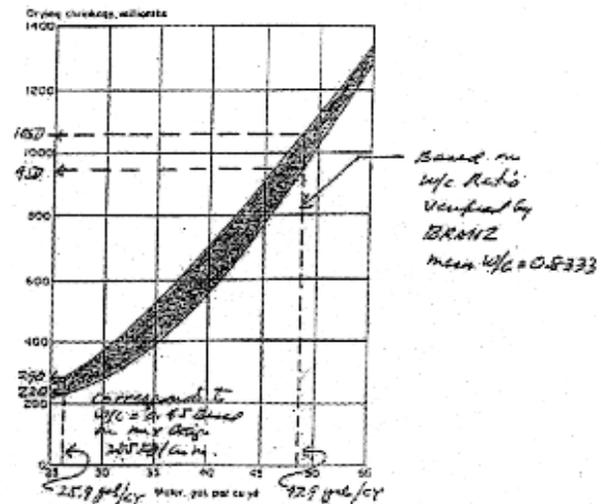


Fig. 13-8. Relationship of total water content and drying shrinkage. A large number of mixtures with various proportions is represented within the area of the band curves. Drying shrinkage increases with increasing water contents. 1 gal = 8.34 lb of water.

<sup>41</sup> Steven H. Kosmatka and William C. Panarese. "Design and Control of Concrete Mixtures". Thirteenth Edition. Portland Cement Association, Old Orchard Road, Skokie, Illinois.

<sup>51</sup> Kong. "Handbook of Structural Concrete". ACI Method 209 Shrinkage Correction Factors. Fig. 2-7- Chapter 11, -age 12, Pitman Publishing, Inc., Mass. 1983.

<sup>31</sup> The standard conditions are based on US conditions.

Based on these charts, and with the following actual data:

W/C Ratio As Specified 0.42                      **25.9**  
 Resulting Water Content is                      gallons/CY

W/C Ratio actually poured  
 Determined from average of  
 Lab test W/C=0.8333

The resulting Water Content is                      **47.9**  
 (Computed from submittal                      gallons/CY  
 of Mix Design

From these values, the Upper Band of the curve is entered to yield the following shrinkage magnitudes:

*Shrinkage Value  
 In millionths*

As specified W/C = 0.42                      290  
  
 As poured and determined  
 By New Zealand Lab  
 W/C<sub>Ave</sub> = 0.8333                      1,020

There is significantly, a lesser shrinkage value based on the specified W/C of 0.42 over “normal” concrete and a very large increase in the case of excessive W/C as provided (W/C=0.833 provided vs. W/C=0.42 specified).

The values obtained, 290 microstrain or **0.29mm/meter** and 1.020 microstrain or 1.02 mm/meter are used as base or reference figure in predicting quantitatively the actual shrinkage magnitudes in this specific case using ACI 209 procedures. The effects of various other factors can be introduced further.

It can be seen from the above that the actual Ultimate Shrinkage Strains ( $\epsilon_{SH\infty}$ ) produced by the as poured concrete (W/C=0.8333) is **251.7%** greater than for the specified concrete (**0.290 vs. 1.020 mm/meter**).

If the shrinkage correction factors as prescribed by **ACI 209** are applied, the resulting Actual Shrinkages would be:

	$\epsilon_{SH\infty}$	Product of Shrinkage Correction Factors	Ultimate Shrinkage Values
Concrete As Specified W/C=0.42	0.290 mm/meter	0.3654	0.1060 mm/meter
Concrete As Poured W/C=0.8333 (Contractor)	1.020 mm/meter	0.3654	0.3727 mm/meter

## 1.2 Prediction of Shrinkage at any Time Based on ACI 209R-92

Shrinkage prediction at any time after age 7 days for moist cured concrete is given by equation 2-9 **ACI 209R-92** as follows:

$$(\epsilon_{SH})_t = \frac{t}{35+t} (\epsilon_{SH})_u$$

where:

- $(\epsilon_{SH})_t$  = Shrinkage at any time (t)
- t = Time in days after the end of initial Wet curing
- $(\epsilon_{SH})_u$  = Ultimate shrinkage value

This equation is a very powerful tool in quantifying the actual magnitude of shrinkage at any time but more importantly during the moist critical stage of strength development when the concrete has not yet fully attained its design strength.

Using the above Equation 2-9 with a curing period of 14 days as specified, the following shrinkage strain factors are generated for various times beyond the 14 day initial wet curing period.

Period	Time Days	Shrinkage Correction Value
1	0	0
2	5	0.125
3	15	0.3
4	25	0.416667
5	35	0.5
6	45	0.5625
7	85	0.708333
8	105	0.75
9	125	0.78125
10	165	0.825
11	205	0.854167
12	215	0.86
13	365	0.9125
14	8000	0.995644

What the foregoing data portray is that the shrinkage value attained at approximately one year (365 days) is 0.91 of the ultimate shrinkage value. More importantly it shows that shrinkage strain development is gradual and does not reach peak value until a considerable period of time has elapsed.

This is very crucial in determining and quantifying what actually happened to the slab when these were reported to have cracked after approximately one month after pouring.

## 2.0 SIGNIFICANCE OF CALCULATION RESULTS

Based on calculations consistent with ACI 209R, the following conclusions can be made:

- 1) The as specified concrete with W/C=0.42 will not exceed the Allowable Tensile Strain Capacity of unreinforced concrete at any time.  
( $\epsilon_{SH0} = 0.1060 \text{ mm/meter}$  vs.  $\epsilon_{SH\text{Allowable}} = 0.150$  to  $0.200 \text{ mm/meter}$ ).
- 2) The as poured concrete exceeded the Allowable Tensile Strain Capacity even initially at approximately 30 days after wet curing (*almost exactly at the same time the first cracks were observed*).  
( $\epsilon_{SH0} = 0.3727 \text{ mm/meter}$  vs.  $\epsilon_{SH\text{Allowable}} = 0.150$  to  $0.200 \text{ mm/meter}$ ).

The results **underscore** the effectiveness of the shrinkage control measures that have been specified by this Engineer of Record to limit the strains to tolerable values have the correct W/C been followed.

It is not correct to use any other data such as “**Approximately 0.35mm/meter**” as the actual strain since this is not representative of the actual conditions and remain merely as baseless assumptions.

In truth, the actual magnitude is very much less than this prediction, due to the effect of very low W/C specified and other measures used to control shrinkage.

The results of the calculations for predicting the actual magnitude of the Ultimate Shrinkage  $\epsilon_{SH}$  based on **ACI 209R-92** (*Section 3.0*) and the prediction of the rate of development of shrinkage with time (*Section 2.0*) also from **ACI 209R-92** where graphically presented in order to present a clearer picture of what actually happened and what was the real cause of shrinkage.

*Note: This is consistent with the Field observations that the cracking occurred approximately one month after pouring.*

### 2.1 Plastic Shrinkage Stage

At the critical stage when plastic shrinkage was happening (*1-3 days*) the corresponding strengths are as follows:

As poured Concrete (W/C = 0.8333)	<b>980 psi</b>
Concrete (W/C = 0.42 as specified)	<b>2,450 psi</b>
Concrete ( $f'c = 3,000 \text{ psi}$ “min. floor” specs.)	<b>1,470 psi</b>

Thus, it can be seen that strength development at the critical Plastic Shrinkage Development would have been adequate for the specified W/C Ratio and is more than **2.5 times** that of the as poured concrete.

Thus, the as poured concrete had very low available strength because of the very high W/C Ratio and is inadequate to resist plastic shrinkage cracking.

### 2.2 Curing Stage

For the specified 14 day curing period, drying shrinkage is not yet developing, for this reason the time scale for strain development is offset by 14 days.

What this mean in simple language is that the drying shrinkage is postponed until after the wet curing period of 14 days.

During this time, and because the area is fully enclosed, humidity built up, because of the wet curing procedure and due to the absence of air movements.

### 2.3 Drying Shrinkage Period

Beyond the 14 day Wet Curing specified, shrinkage strains from drying started to set in and the development is predicted by *Equation 2-9* of **ACI 209R**.

Despite the high relative humidity inside the pouring area, it was not enough to arrest cracking of the as poured slab due to the very high shrinkage potential from the excessive water content of the as poured slab, something clearly illustrated by CHART ‘A’ which is a graphical presentation of the calculation results.

### 3.0 Closure

The foregoing calculations for an actual problem have shown that shrinkage stresses can be calculated and that the shrinkage is excessive and beyond that have occurred tolerable limits due to the high water cement ratio W/C of the as laid concrete in violation of the specs.

The rational formulas as prescribed by ACI Committee 209 is an invaluable tool in determining the magnitude of shrinkage strains in the concrete which are indisputable if the actual conditions are used.

# CHART "B"

## STRENGTH DEVELOPMENT AND STRAIN GRAPH OF UNREINFORCED CONCRETE

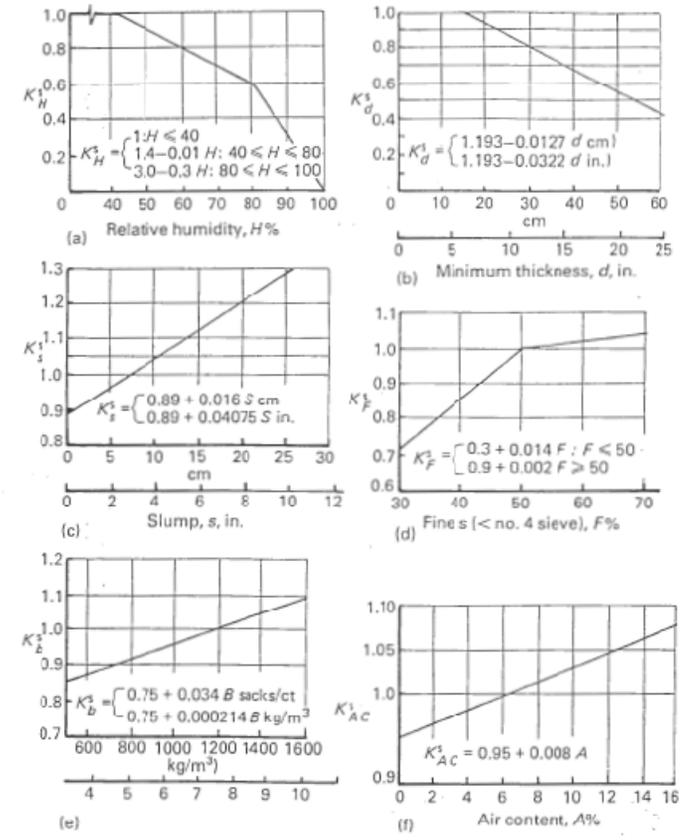
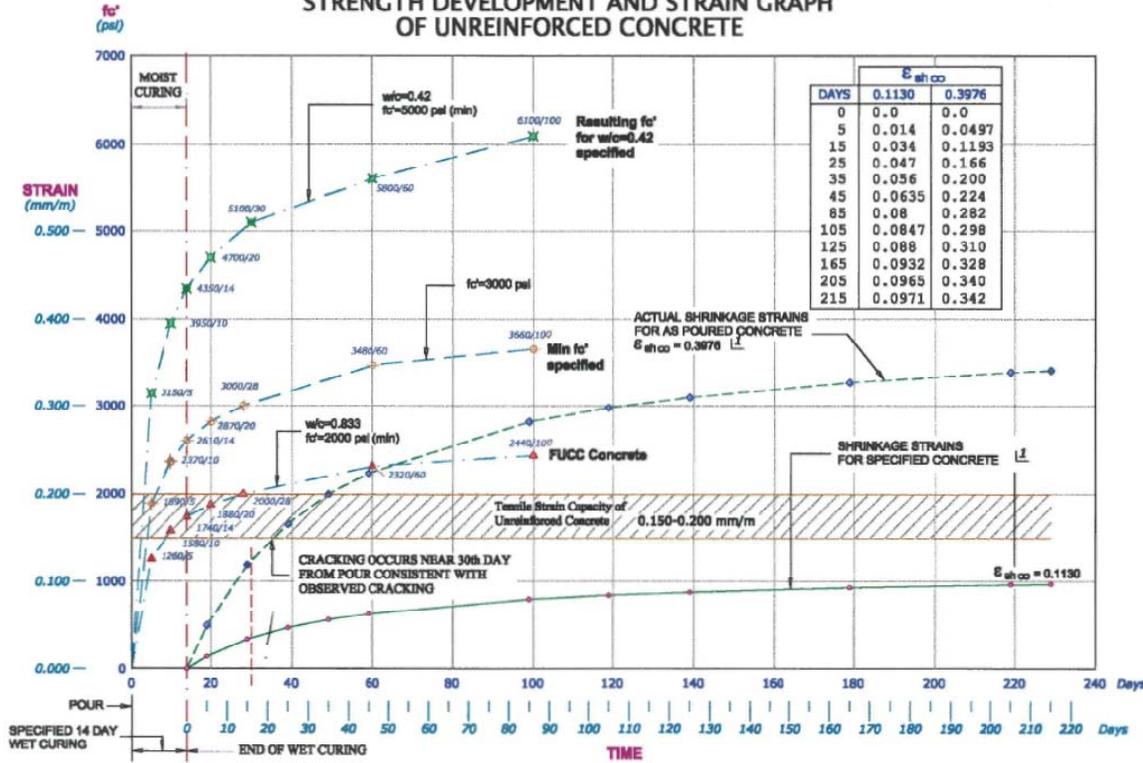


Figure 2-7 Shrinkage correction factors for the ACI 209 method of shrinkage prediction. Note that at standard conditions  $K^1 = 0$

- (a) Ambient relative humidity
- (b) Member minimum thickness
- (c) Concrete consistency
- (d) Fine aggregate content
- (e) Cement content
- (f) Air content