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Comparison of theoretical and experimental shrinkage in concrete

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HIGHLIGHTS

- ACI 209 and B3 models showed good shrinkage prediction in specimens cured at 28 °C and 50% R.H.
- Best predictions at 50 °C and 5% R.H. were by GL2000 in standard specimens and CEB-FIP in plain prisms.
- Effect of size on shrinkage strains increases as curing temperature increases.
- ACI 209 and Sakata models show good prediction of specimen size effects at 28 °C and 50% R.H.
- Inaccurate prediction is shown by assuming constant size effects for different drying conditions.

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ABSTRACT

There are several models developed to predict shrinkage strains in concrete. These models are adopted by various codes or suggested by prominent researchers. The results of experimental measurements of shrinkage strains in plain concrete are compared to the theoretical shrinkage strains predicted using five available models which are: ACI 209, CEB-FIP, B3, Sakata, and GL2000. Measurements were taken on standard specimens (50 × 50 × 300 mm) and plain prisms (80 × 150 × 500 mm) subjected to moderate curing condition (28 °C and 50% R.H.) and a harsh curing condition (50 °C and 5% R.H.). ACI 209 and B3 models were found to have good prediction of experimental shrinkage strains in specimens cured in humidity room while GL2000 and Sakata models showed poor approximations. The best approximation of experimental shrinkage in standard specimens that are cured in temperature room are shown by GL2000 model while CEB-FIP model shows the best prediction in plain concrete prisms that are cured in temperature room. The effect of the considered specimen sizes on shrinkage strains is moderate when cured in humidity room while the effect is noticeable in specimens cured in temperature room. ACI 209 and Sakata models show good quantifications in specimens cured in humidity room and the predicted effect of specimen size in temperature room is far from the experimental effects for all models. All models assume constant and similar size effects on shrinkage for all type of drying conditions which cause inaccurate prediction.

1. Introduction

Shrinkage in concrete is a time dependent deformation phenomenon. It can be defined as the reduction in volume of unloaded and unrestrained concrete element at a constant temperature. The main cause of such deformation is the loss of water during the drying process of concrete. The contraction of a certain structural concrete member is restrained by its own steel reinforcement, its supports, or another structural member. The presence of shrinkage and restraint together imposes tensile stresses inside structural concrete elements. Since concrete is weak in tension resistance, these stresses lead to the development of cracks in concrete. This kind of time dependent deformation in concrete, if not controlled, can affect the serviceability [1–3], durability [1–5], and stability [2] of structures and also can lead to even shear strength failure [1].

Precise and reliable prediction models of shrinkage strains are required to achieve the design objective of serviceability in the design of structural members. Amadio and Fragiacomo [6] state that correct assessments of shrinkage time effects on stress and deflection response is very important in order to check the serviceability limit state. They also add that shrinkage behavioral prediction forms that follow the actual behavior of concrete are very complex to be adopted and the exact solution can only be determined for a very simple structure schemes. Bazant and Baweja [7] have stated that the accurate prediction of shrinkage in concrete is difficult because of the phenomenon involves several interacting physical mechanisms and is affected by many factors.

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Various analytical models have been developed to predict shrinkage strains in concrete and some of them are adopted by various codes and suggested by prominent researchers. In this paper, the results of shrinkage strains obtained by theoretical prediction models are compared with shrinkage strains obtained from experimental testing [8]. Measurements were taken on standard specimens ($50 \times 50 \times 300$ mm) and plain prisms ($80 \times 150 \times 500$ mm). A controlled humidity room (28 °C and 50% R.H.) that represents a moderate curing condition and a controlled temperature room (50 °C and 5% R.H.) that represents a harsh curing condition were considered. Half of the tested samples were with a plasticizing admixture and the other half were without the admixtures.

2. Available prediction models

Calculation of concrete deformations due to shrinkage is difficult. The behavioral prediction forms that follow the actual behavior of concrete are very complex to be identified since such phenomenon is an interaction of several physical mechanisms influenced by many parameters. Extensive research has been conducted to quantify and predict the effect of concrete deformation including shrinkage. Various empirical and analytical models have been developed to predict shrinkage. The most utilized shrinkage prediction models in current standard codes are described below and considered for the comparison with the experimental results.

2.1. ACI 209 model

The American Concrete Institute (ACI) proposed in 1982 an empirical model to predict shrinkage strains [9]. The model is applicable to normal and light weight concretes under the standards conditions listed in Table 1. The shrinkage strain expression that is recommended by the ACI-209R-82 codal provisions is as follows:

$$\varepsilon_{sh}(t, t_c) = \frac{(t - t_c)}{T_c + (t - t_c)} \varepsilon_{shu} \quad (1)$$

where $\varepsilon_{sh}(t - t_c)$ is the shrinkage strain at any time t, micro, mm/mm, t the age of concrete at time of interest, days, t_c the 7 days for moist cured concrete and 1–3 days for steam cured concrete, T_c the 35 days for moist cured concrete and 55 days for steam cured concrete and ε_{shu} is the notional ultimate shrinkage strain (780×10^{-6}) for standard conditions.

There are different conditions of the experimental testing other than the standard conditions that are related to relative humidity and volume to surface ratio. Therefore, correction factors for conditions other than standard conditions have to be considered. The adjustments for these two variables are as follows:

Shrinkage correction factor for relative humidity = 1.4–0.0102 R.H, $40 \leqslant$ R.H $\leqslant 80$.

It is assumed that the correction factor = 1.1, for relative humidity less than 40%. Shrinkage correction factor for volume to surface ratio is given as: $1.2e^{(-0.00472v/s)}$. In these expressions R.H. is the relative humidity in % and v/s is the volume to surface ratio in mm.

Table 1
Standard conditions for shrinkage prediction using ACI 209.

Parameters	Standard conditions
Type of cement	Type I and III
Slump (mm)	70
Air content (%)	$\leqslant 6$
Fine aggregate (%)	50%
Cement content (kg/m^3)	279–446
Moist cured (days)	7
Steam cured (days)	1–3
Temperature of moist cured (°C)	23 ± 2
Temperature of seam cured (°C)	$\leqslant 100$
Relative humidity (%)	40
Concrete temperature (°C)	23 ± 2
Volume to surface ratio (mm)	38
Or minimum thickness (mm)	150

Table 2
Input parameters for theoretical shrinkage strain models.

Shrinkage model							
Parameter	Unit	Specimens	ACI 209	CEB-FIP	B3	Sakata	GL2000
Width	mm	STANDARD	50	50	50	50	50
		PRISMS	80	80	80	80	80
Height	mm	STANDARD	50	50	50	50	50
		PRISMS	150	150	150	150	150
Length	mm	STANDARD	300	300	300	300	300
		PRISMS	500	500	500	500	500
t_c	days		7	7	7	7	
T_c	days		35				
β_{sc}				4			
f_{cm}	Mpa			30.7	30.7	30.7	30.7
RH	%	Humidity room	50	50		50	
h	decimal				0.5		0.5
RH	%	Temperature room	5	5		5	
h	decimal				0.05		0.05
A_c	mm^2	STANDARD		2500			
		PRISMS		12,000			
μ	mm	STANDARD		200			
		PRISMS		460			
α_1					1		
α_2					1		
ω	Kg/m^3				178	178	178
k_s					1.25		
V	mm^3	STANDARD	750,000		750,000	750,000	750,000
		PRISMS	6,000,000		6,000,000	6,000,000	6,000,000
S	mm^2	STANDARD	65,000		65,000	65,000	65,000
		PRISMS	254,000		254,000	254,000	254,000
K							1