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Long-term Shrinkage Empirical Model of High Performance Concrete in Humid Tropical Weather

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Abstract

This paper represents a long-term shrinkage empirical model of high performance concrete (HPC) with and without fly ash based on experimental research in which compressive strength was 60MPa. Specimens measuring 150x150x600 mm^3 were used. Observations were conducted over the two year periode using an embeded vibrating wire strain gauge. As a result, the empirical model was in agreement with experimental results. Addicionally comparisons were made with ACI 209R, AS 3600-2009 and Eurocode 2. The results showed that ACI 209R was about 60% and 75% of HPC with and without fly ash respectively. Eurocode 2 was underestimated for both HPC (58%) and HPC without fly ash (73%). AS 3600-2009 was 16% higher than HPC with fly ash but this condition is suspectable to change during longer observation periode because AS 3600-2900 has a lower slope than the empirical model, while HPC without fly ash was overestimated (93%). Model representation shows significant differences in form compared to ACI 209R; and AS 3600, and similarity in form compared to Eurocode 2.

Keywords: Shrinkage, High performance concrete, Empirical model, Humid tropical weather

1. Introduction

The most difficult, uncertain and risky aspect in designing a concrete structure is the prediction of time-dependent behavior. Along with the development of the construction industry, the use of high performance concrete is also developing. High performance concrete (HPC) is often defined as concrete with a compressive strength exeeding 60 MPa and a resistance to damaging influences (Nishiyama, 2009). More cement is used in HPC than in normal concrete, but the use of water is much lower. Therefore, the low water to cementitious ratio causes refined pores, and the HPC is more sensitive to cracking at early shrinkage than normal concrete, even when good curing is applied. A better understanding of long-term shrinkage will ensure good performance of the concrete structure during its service-life.

Drying shrinkage is influenced by external supply water, so climate plays an important role especially in long-term shrinkage. All of the regulations have inserted humidity and temperature as shrinkage factors, except for ACI 209R and AS 3600-2009, which do not include temperature as a shrinkage factor. Because the hydration process may occur in 416 days (Morin,Cohen-Tenoudji,Feylessoufi, and Richard,2002), drying shrinkage may occur simultaneously with hydration, causing the shrinkage mechanism to be complex.

Just as approximately 60% of research studies about shrinkage refer to ACI, the concrete design code in Indonesia refers to ACI too, it is based on research studies from four-season countries, despite some significant differences that are displayed in Figures 1 and 2 in below.

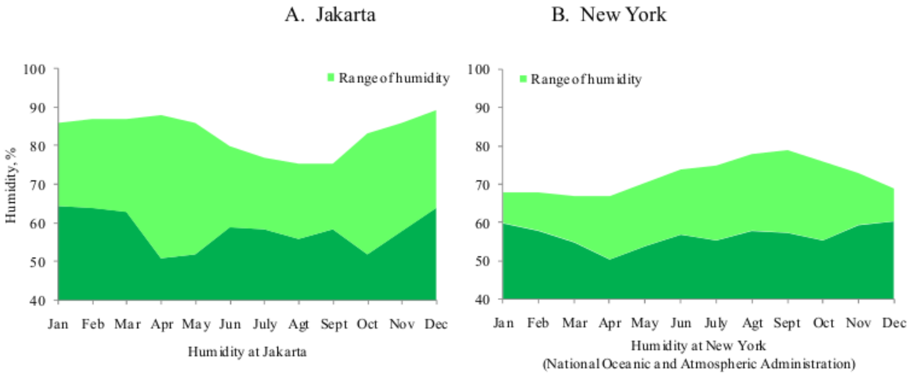


Figure 1. Relative humidity at Indonesia and New York.

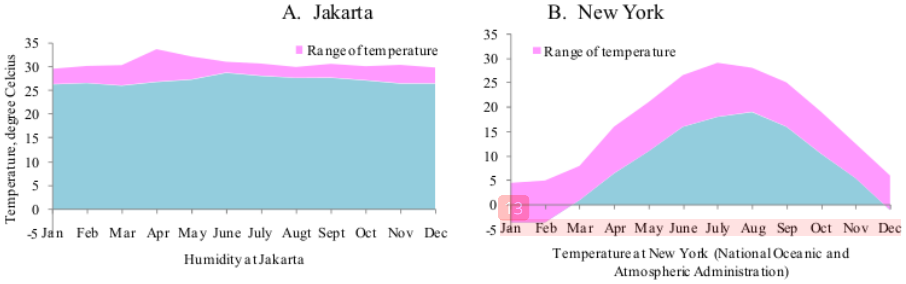


Figure 2. Temperatures in Indonesia and New York.

Figure 1A and 2A were obtained by investigating temperature and humidity in the morning and in the afternoon from November 2009 until December 2011, at the University of Indonesia, Jakarta, Indonesia (humid tropical climate). Figure 1B and 2B were taken from National Oceanic and Atmospheric Administration (NOAA) as representative of four-seasons climates. The range of minimum and maximum humidity in humid tropical weather compared to four seasons countries is about 2 times with the average of 72% (Fig.1). Figure 2A shows that the temperature in humid tropical weather is high throughout the year; this condition is significantly different from temperatures in four-season countries (Fig. 2B).

Many researchers have focused their attention on concrete shrinkage. Altoubat and Lange, (2000), and Guo, Sause, Frangopol, and Li (2011)] studied shrinkage at the early age. Omar, Omar, Ashikin, Khairussaleh, and Shahreen Ab Wahab (2010) investigated shrinkage of normal concrete in tropical weather over 180 days. Omar, Makhtar, Lai, Omar, and Ng (2008) also studied the influence of ground-granulated blast- furnace slag on shrinkage. Park, Noguchi, and Kim (2006) observed shrinkage in HPC during a 6 day periode, and Pons, Munoz, and Escadeillas (2003) investigated shrinkage in normal concrete over 1.000 days. Kanganpanich (2002) studied shrinkage in self-consolidating concrete. Results for shrinkage cited in research studies compared to codes area as follows:

- AASHO LRFD was in agreement for moist-cured concrete (Mertol, Rizkalla, Zia, & Mirmiran, 2010; Kartikeyan, Upadhyay,& Bhandari,2008),
- AASHO LRFD was over estimate for heat-cured concrete (Mertol et al, 2010),
- ACI was not accurate (Goudousi, Afsar, Ketabchi, & Rasa, 2009; Canfield, 2005; Yeol Choi 2004, Carlos Videla, 2004; Slapkus, 2002; Huo, 2001).

Mertol et al. (2010) conducted a 2-year investigation but the others are observed for less than a year with research conditions in which temperature was about 22°C and relative humidity was about 50%. According to Pihlajavaara (1974), shrinkage can be strong in relative humidity (RH) of 50-80%, and 0-20%, and minor in RH of 20-50%. Based on this observation, Indonesia and New York are situated in strong shrinkage areas, although Indonesia has ±10% higher shrinkage than New York. The influence of tropical weather, based in by AS 3600-2009 and Eurocode 2, allow a correction factor of 0.5, and 0.7 respectively, to the drying shrinkage formula, while the correction factor in ACI 209R is 0.68 to total shrinkage.

The above research studies indicate that there are large variations in shrinkage behavior. Observations conducted for less than 416 days have not yielded a fully understanding of long-term shrinkage behavior which is truly needed to design concrete with strong performance levels. Regarding the high-strength concrete that was developed rapidly in the Asia region during the past two decades, many of it's concrete properties have not been widely known; for example, it's long-term shrinkage properties in humid tropical regions of Indonesia and South-east Asia should be studied future.

Fly ash as cementitious material in concrete in the world was widely use. Boga and Topçu (2012) studied the influenced of fly ash in concrete; the amount of 15% fly ash in the mixture showned higher compressive strength and splitting-tensile strength than 30% or 45% fly ash. With water cured treatment on specimens, 15% fly ash incurred less corrosion than 30% fly ash as the cement replacement.

The objective of this research was to create an empirical model for describing long-term shrinkage of HPC with and without fly ash in humid tropical weather. We anticipate that the results will provide a better understanding regarding HPC shrinkage behavior in humid tropical weather.

2. Materials and Methods

This research was performed experimentally using 6 specimens of 150x150x600 mm^3, according to ASTM C78-08 with one vibrating wire embedded strain gauge (VWESG) per specimen. The position of the VWESG can be seen in Figure 3A, (i.e., 5 cm from the end of the specimen). High performance concrete with target compressive strength of 60 MPa and slump flow diameter of 35±2 cm was used for the specimens (Fig.3B) Specimens were produced with two variations: addition of fly ash and referred to as triple blend (TB) meaning that cement was added using silica fume together with fly ash and without the addition of fly ash, and referred to as double blend (DB), meaning that cement was added using silica fume without fly ash.

2.1 Materials

The mix design was conducted in compliance with ACI 211.4R with a limit of 500 kg/m^3 cement content to meet the shrinkage factor closest to 1 (ACI 209R, 1992). Ordinary Portland Cement (OPC) produced by Indocement Ltd was used. Condition of the aggregate was saturated surface dry (SSD). Fine aggregate in the form of river sand was brought from in from Sungai Liat (Bangka, Sumatra, Indonesia); specific gravity (SSD) was 2.6053; and absorption was 0.4%. The sand had been filtered and cleaned using a mixture of standard graphs obtained from the mid-gradation, according to ASTM C.33/C.33M-08. Coarse aggregate in the form of volcanic rock fragments was obtained from Banten, West Java, Indonesia. Composition of the coarse aggregate used was 70% size of 13-19mm; specific gravity (SSD) was 2.563; absorption was 1.543%; and 30% size of 6-12mm; specific gravity was 2.636; and absorption was 2.26%). Type F fly ash according to ASTM C618-8a is a waste material from the electrical power plant in Suralaya, West Java, Indonesia. In this mix design, 15% fly ash was the cement replacement. Added material used was silicafume of 8% cement weight of DB produced by Sika Indonesia Ltd. To achive the desired high strength with low water to cementitious material ratio and good workability, polycarboxylic superplasticizer under the commercial name ViscoCrete ® 10 from Sika Indonesia Ltd was added to the concrete mix as high range water reducer (HRWR). The dose of HRWR of 1.4% cement weight was according to that generally used in Indonesia. Local water was supplied by the Structure and Material Laboratory of University of Indonesia. An electrical scale was used especially for cementitious materials and water to obtain the accurate water to cementitious material ratio.

Materials composition are displayed in Table 1.

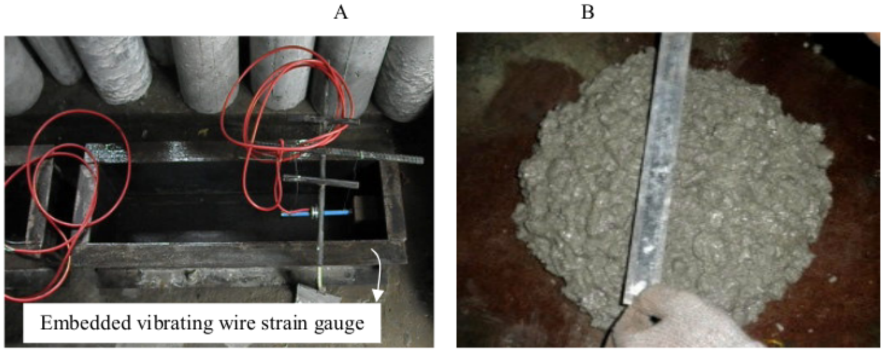
Table 1. Mix composition

Material (*kg/m*^{3})	Without fly ash (DB)	With fly ash (TB)
OPC	500	454.3
Silica fume	40	40
Fly ash		57.14
Water	142.6	146
Sand	800	800
Coarse aggregate	935	935
HRWR	7.6	7.6

In order to achieve similar shrinkage using aggregate, fine and coarse aggregate for both mixtures were similar. During the concrete mix design stage, all of the aggregate was assumed to be under saturated surface-dry condition. A tilting drum mixture of 0.3 m^3 capacity was used. The mixing started with all cementitious material in dry condition, followed by 50% fine aggregate. Subsequently, 50% water was added to the revolving mixture. These materials were then mixed for approximately 1½ minutes. Next, 50% water was slowly poured in, which mixed with HRWR homogenously. Thereafter 100% coarse and 50% fine aggregate was added. With all the materials placed according to its order into the mixer, the concrete was mixed for approximately 3 minutes. The slump flow of the mixture was measured before pouring by using Abram's cone with upside down position.

2.2. Methods

Shrinkage was measured as strain change against time by installing VWESG in the specimen. The VWESG has abilities to detect the strain up to 3000 $\mu\varepsilon$ with accuracy of about .025% and concrete temperature between -80°C and 60°C with about .5% accuracy (Fig. 3A).



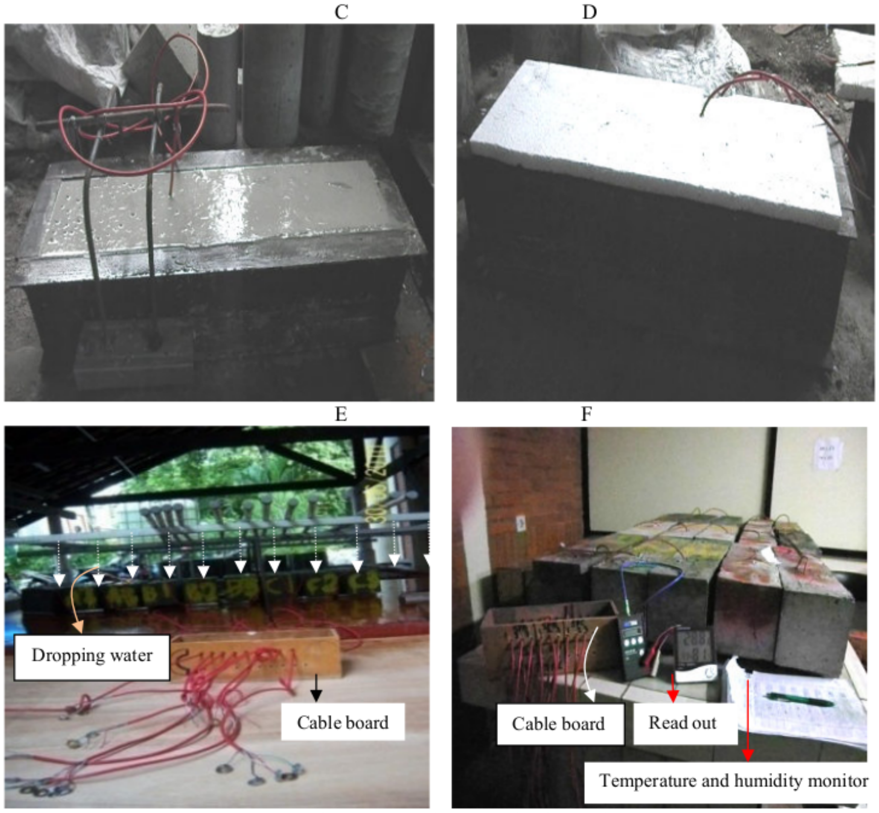


Figure 3. Specimen production and treatment.
3A. Mold with VWESG; 3B. Slump flow; 3C. Specimen after casting;
3D. Specimen with styrofoam covering; 3E. Wet curing; 3F. Specimen in conditioned room

Right after casting (Fig. 3C), specimens were covered with styrofoam to eliminate water evaporation (Fig.3D). The specimens were cured after demoulding (one day after casting) by droping water on the specimens to the age of 7 days. (Fig. 3E) . After this treatment, specimens were placed in a conditioned room with temperature of 28±3°C and relative humidity of 72±5% relative humidity (Fig. 3F).

Observations was performed righ after pouring as follows: 0-24 hours, every 15 minutes; 24-48 hours, every 60 minutes; days 3-7, every 2 hours; and one time each day using a read out (Fig. 3F). Crack observations were performed using a loop 50 times larger.

Datas from 3 specimens of DB and also TB were analyzed using Dixon's criteria as the standard practice for dealing with outlying observation according to ASTM E 178-02 for data at ages 50, 100, 200, 300, 400, 500, 600, and 700 days, with a significant level of 5%. Based on the average of accepted data, the empirical model was performed. The agreement between model and experimental data was obtained by computing the error and investigating the w/s value during observations and comparing it with w/s critical value [ASTM E 178-02]; where "w" was deviation of error at time t and minimum error during observation, and "s" was the standard deviation. "Error" refers to a deviation between the empirical and experimental models.

3. Results

The results of this research are mainly divided into two parts; compressive strength and long-term shrinkage behavior.

3.1 Compressive Strength

Compressive strength of both mixture are shown in Figure 4.

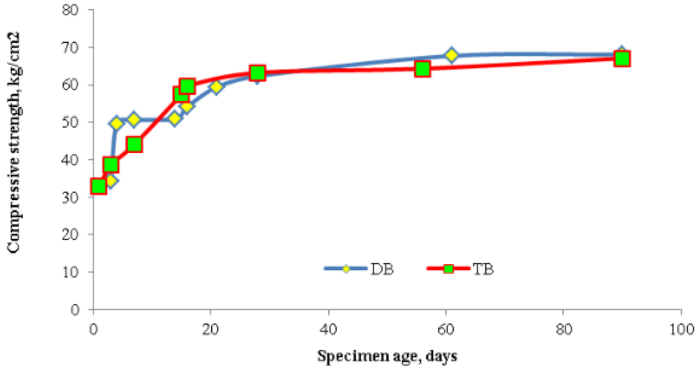


Figure 4. Compressive strength.

3.2 Long-term Deformation

The results for three specimens of DB and three specimens of TB are as follows:

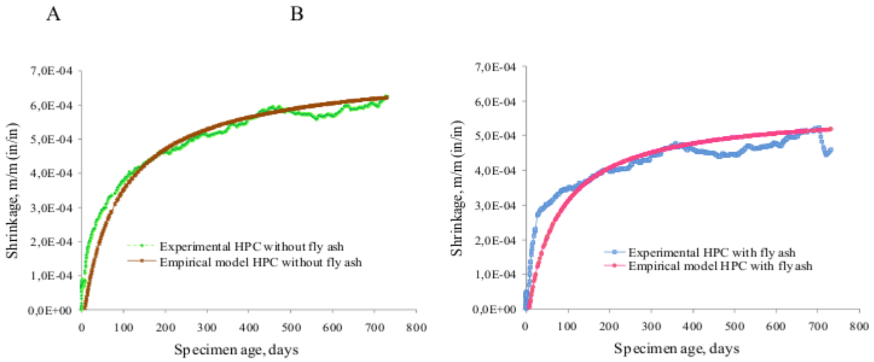


Figure 5. Experimental and empirical model of HPC
5A. Without fly ash (DB); 5B. With fly ash (TB).

The empirical model as shown in Figures 5A and 5B was found to be:

$$\varepsilon_{sh} = [[t/(C+t^{\alpha})]\varepsilon_{(sh)u}]^{p} \qquad (1)$$

where:

ε_{sh} : shrinkage strain
$\varepsilon_{(sh)u}$: ultimate shrinkage strain, 587×10^{-6} for HPC without fly ash and 499×10^{-6} for HPC with fly ash

t : time after curing
C : 50 for HPC without fly ash; 45.2 for HPC with fly ash
α : 0.98 for HPC without fly ash;0.992 for HPC with fly ash
p : 1 for HPC without fly ash; 1.009 for HPC with fly ash

4 Discussion

A cement replacement of 15% fly ash shown similarity of compressive strength between DB and TB

(Fig. 4).

4.1 Analysis of specimen data

Datas from three specimens of DB and three specimens of TB are shown in Figure 6 below.

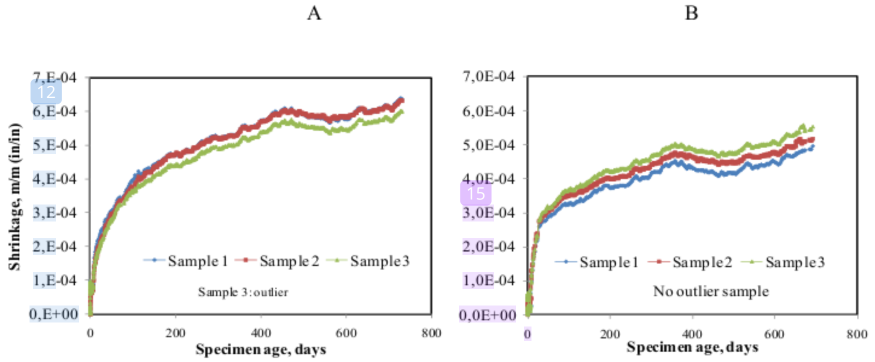


Figure 6. Experimental results of shrinkage.
6A. Without fly ash (DB); 6B. With fly ash (TB)

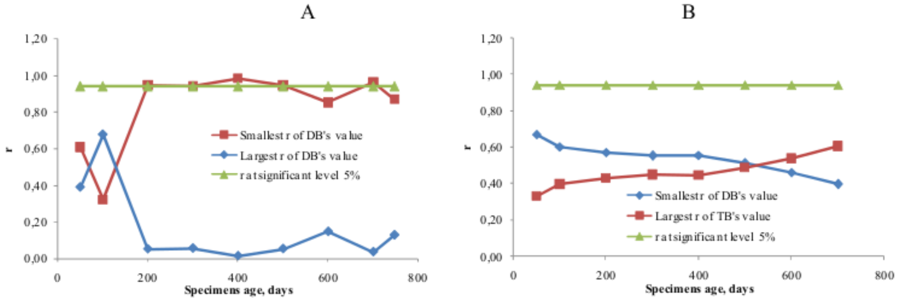


Figure 7. Outlying analysis.
7A. Without fly ash (DB) 7B. With fly ash (TB)

Verification of data from three specimens was conducted at ages 50, 100, 200, 300, 400, 500, 600, 700 days in compliance with Dixon's criteria of ASTM E178-02, as shown in Figure 7. Figure 7A illustrated that the smallest data values of the DB specimen were the outliers at 400 and 700 days with a significance level of 5%; therefore, the data from this specimen were not considered in the next computation. Figure 7B shows that no data were identified as outliers. DB and TB shrinkage were assumed as average values from accepted data, as shown in Figure 5.

4.2 Comparison between experimental and empirical models

Comparison between experimental and empirical models can be seen in Figure 5.

To understand the quality of the proposed empirical model, it was tested according to two methods. The first methods was conducted according to ASTM E 178-02 by comparing w/s at time t and w/s critical at the 5% significant level (Table 3) of ASTM E 178-02. The second method was conducted to evaluate the error during observations. Validation test results are displayed in Figure 8 below.

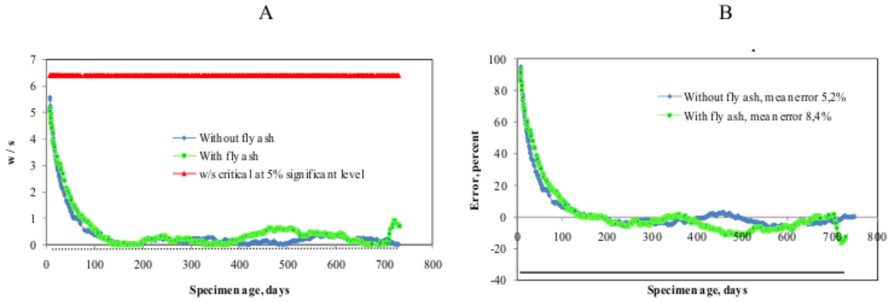


Figure 8. Validation of the model
8A. Validation using ASTM E178-02 (w/s critical) 8B. Validation using error value

During observation, the w/s was smaller than w/s critical, so the empirical model was accurate enough; even at 7 to 90 days the w/s was greater than 1, as shown in Figure 8A. The deviation between shrinkage by model displayed in Figure 8B. At 7 to 90 days the model had a large deviation; beyond that periode, the deviation became smaller. The mean errors of HPC without fly ash and with fly ash were 5.2% and 8.4% respectively, so the model sufficiently to describes long-term shrinkage behavior.

4.3 Comparison of shrinkage between HPC with and without fly ash

Shrinkage comparison between HPC with and without fly ash can be seen in Figure 9.

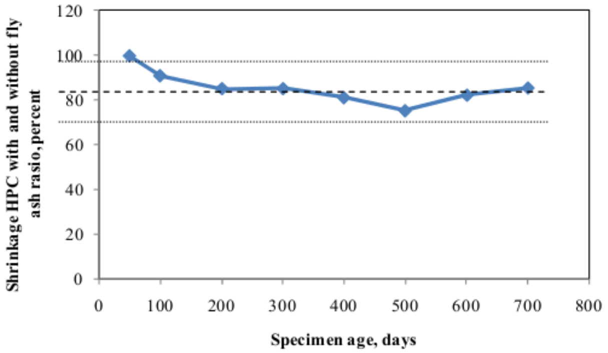


Figure 9. Shrinkage ratio between HPC with and without fly ash over time.

On the average, shrinkage in HPC with fly ash (Fig. 9) in long-term periods was about 82% of shrinkage in HPC without fly ash. Smaller grains of fly ash filled the concrete pores, thus the concrete appeared to be more solid than without fly ash.

4.4 Comparison of the empirical model with ACI 209R, Eurocode 2, and AS 3600

Comparisons between the experimental model, empirical model, ACI 209R, Eurocode 2, and AS 3600 can be seen in Figure 10.

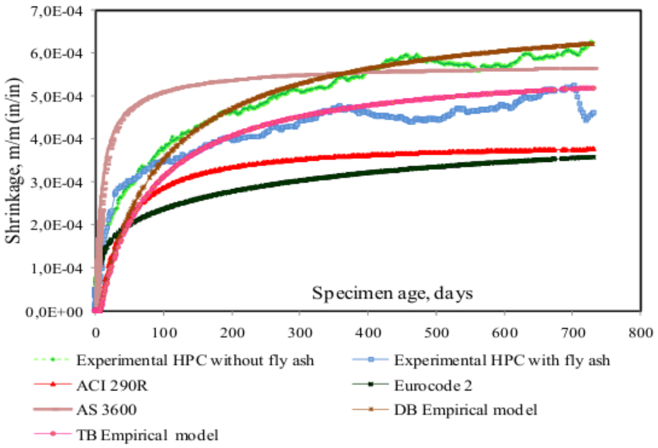


Figure 10. Comparison between experimental model, empirical model, ACI 209R, Eurocode 2, and AS 3600.

Figure 10 shows that Eurocode 2 and ACI 209R were underestimated for HPC with and without fly ash, while AS 3600 was overestimated for TB but underestimated for DB. In long-term periods the two types of HPC showed non-asymptotic behavior similar to Eurocode 2, while AS 3600 and ACI 209R showed asymptotic properties (Fig. 10). Non-asymptotic form means the shrinkage still develops, especially drying shrinkage. The main emphasis of this research was to assess the effect of the humid tropical environment on time-dependent deformation because of shrinkage in concrete; appropriatly non-asymptotic form is a special behavior which distinguishes long-term deformation in humid tropical and non-humid environments. The deformation happens continously, even when the hydration process last longer than 416 days (Morin et al,2002). Based on this phenomenon, it was appropriate for this analysis to stress drying shrinkage.

Relative humidity to be a single parameter in final unrestrained drying shrinkage values for concrete. If the parameter multipled by the time and a factor of dimension, by using power on the time so the Formula become drying shrinkage formula in Eurocode 2. Similar to Eurocode 2, AS 3600 inserted the influence of the environment as a single factor but in a global condition such as arid, interior, temperate inland, tropical or near coastal environment (AS 3600, 2009). The slope in Eurocode 2 is similar to the slopes of HPC with and without fly ash (Fig. 10).

At the early age (7-14 days), AS 3600 and Eurocode 2 were in agreement with the experimental results, but the code did not fit during long-term periods. Eurocode 2 and AS 3600 predicted total shrinkage as a sum of early shrinkage and drying shrinkage, while ACI 209R presented total shrinkage as a function of time a simpler formula.

To present a simple model oriented toward prediction of deformation during long-periods, we proposed that the long-term shrinkage behavior is a function of time similar to ACI. The shrinkage formula of ACI 209R is:

$$\varepsilon_{sh} = [t/(35+t)]\varepsilon_{(sh)u} \qquad (2)$$

where $\varepsilon_{(sh)}$ is shrinkage strain, t is time after curing and $\varepsilon_{(sh)u}$ is ultimate shrinkage strain.

In general form, the shrinkage formula can be written as follows:

$$\varepsilon_{sh} = [t/(C+t)]\varepsilon_{(sh)u} \qquad (3)$$

where C is a constant.

The shrinkage of concrete is influenced by the process of cement hydration, called aging. This influence is not confined to young concrete, but through the entire lifetime of structure. The aging is generality described by considering certain material properties to be function of the age, t, of concrete (Bazant & Prasannan, 1988).

To create the empirical model, an understanding about the mechanism in concrete was required. The mechanism was assumed by revision of solidification theory. Solidification theory in which the aging is explained and modeled by the volume growth (into the pores of hardened Portland cement paste) of a nonaging viscoelastic constituent (cement gel), can not explain long-term aging because the volume growth of the hydration products is too short-lived. Revision of solidification theory in which the viscosity of the flow term of the compliance function is treated as a tangensial viscosity of a nonlinear viscous power law governing very large and highly localized microstress in the hardened cement paste (Bazant & Prasannan, 1988). Shrinkage after hardening of concrete, is decrease with time of concrete volume [ACI 209R]. The elementary volume, dv(t), which solidifies at t, is assumed to be represented by a layer deposited on the surface of the material that previously solidified from a solution (Bazant & Prasannan, 1988). This mechanism endures continously until stabel.

In the humid tropical region, the absorbed water layer is larger than a single molecule. The full thickness of the absorption layer cannot expand in small pores, and hindered adsorbed water is performed and leads to slippage. Thus, microstresses in humid tropical weather are higher than in four-season countries. The phenomenon causes the shrinkage growth continously throughout long-term periode. Because the existensi the slippage, the compressive stress would not be transferred continuously (disjoining pressure = ρ_d). Therefore, the transfer was accomplished by the porous wall and the solid frame work around the micropores (Bazant & Prasannan, 1988). Stress will arouse non-linear viscous flow which depends on time.

The empirical models were based on the assumption that shrinkage is a performance of continuous flow. Viscous flow may be assumed to follow a power law:

$$\acute{e}_t \quad = c\, S_t^p \qquad (4)$$

where $\acute{e}_t$is total strain; c is constan; S_t is total stress; and p is a power.

To accommodate the stresses which cause the non-linear viscous flow when it slowed in our experiment, t in the lower fraction was given a power named α. Therefore the stres may be assumed as:

$$S \quad = [t/(C+t^\alpha)] \qquad (4a)$$

$$c \quad = \varepsilon_{(sh)u} \qquad (4b)$$

The formula may be assumed as :

$$\varepsilon_{sh} \quad = [[t/(C+t^\alpha)]\varepsilon_{(sh)u}]^p \qquad (5)$$

where t is time after curing.

The power function is dependent on load duration, age at loading, and current age of concrete. The double power law is in agreement for a very short duration. The triple power law represents a gradual transition from a double power law to a logarithmic creep law. For long-term duration special for basic creep, very good agreement with the measurements, significant improvement is obtained in the representation of the final slope (Bažant & Chern, 1985). In humid tropical weather, capillary forces are larger than those in four- season countries, and they remain almost stable throughout the year, leading to continuous slip development and displayed as non-asymptotic form or slope form (Fig. 10).

The power of HPC without fly ash is 1; for HPC with fly ash, it is 1.009. In this study, the shrinkage mechanism in the mixture with fly ash was more complicated than the shrinkage formula in the mixture without fly ash. The circumstances can be understood because the most significant morphology of fly ash in concrete is developed during the first six months (Wesche,1991).

5. Conclusion

Conclusion from this research include the following:

1) Based on experimental research of long-term shrinkage of high performance concrete in humid tropical weather, an empirical model has been proposed.
2) The empirical model of long-term shrinkage of HPC in humid tropical weather can be written as follows:
   $\varepsilon_{sh}= [[t/(C+t^{\alpha})]\varepsilon_{(sh)u}]^{p}$
   where:
   ε_{sh} : shrinkage strain
   $\varepsilon_{(sh)u}$: ultimate shrinkage strain,
   for HPC without fly as : 587×10^{-6} and
   for HPC with fly ash : 499×10^{-6}
   t : time after curing
   C : for HPC without fly ash : 50 and
   for HPC with fly ash : 45.2
   α : for HPC without fly ash : 0.98 and
   for HPC with fly ash : 0.992
   p : for HPC without fly ash : 1 and
   for HPC with fly ash : 1.009
3) The shrinkage formula is more simple than AS 3600 and Eurocode 2.
4) Results of experimentation showed that ACI 209R and Eurocode 2 were underestimated for long-term shrinkage of DB (cement added using silica fume without fly ash) and TB (cement added using silica fume together with fly ash). AS 3600-2009 underestimated for DB and overestimated for TB.
5) The main difference shrinkage between tropical and four season area is:
   Two years old shrinkage in tropical area is still increasing significantly, in other hand based on ACI 209R and AS 3600, the shrinkage already reached fixed value 350 days and 300 days respectively
6) We have suggested that future research can be connected to the variation of cement and water content to obtain the correction factors for using the above formula with another mixture.

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PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6

PAGE 7

PAGE 8

PAGE 9

PAGE 10

PAGE 11

PAGE 12

PAGE 13