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Accuracy of Shrinkage Prediction Models in High Performance Concretes Containing Slag and Silica Fume

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ABSTRACT

Concrete undergoes time-dependent deformations that must be considered in high-performance concretes (HPC). In this study, four different mixtures were prepared to compare the effect of pozzolanic materials on shrinkage of HPCs. Then, eight existing shrinkage prediction models were assessed to determine which model is the better one. Concrete specimens were made by replacing a part of cement by silica-fume (SF), ground granulated blast-furnace slag (GGBS), and combination of SF and GGBS. Results showed that the total shrinkage was greatly reduced by use of GGBS; and also the accuracy of shrinkage prediction models, depends on the type of pozzolans used in the specimens.

INTRODUCTION

During the last two decades the development and application of HPC has greatly increased in the many parts of the world [Gupta et al. 2006]. To produce HPC, application of super pozzolanic materials such as SF is very usual [ACI 363R-92; Jianyong et al. 1997 and Jianyong and Pei 1997]. Despite advantages of SF, the development of early and later age cracks due to plastic and drying shrinkages are of principal concern. Shrinkage is the decrease of concrete volume with time after hardening of concrete that can lead to cracking in concrete and also, it has a direct influence on prestress losses of prestressed concrete members and the long-term deflection of girders [Huo et al.]. Al-Amoudi et al [2007] and Rao [1998] showed that the accelerated pozzolanic reaction of SF leads to accelerated shrinkage of concrete. In fact, HPC is generally more susceptible to shrink due to higher paste contents and consumption of high reactive pozzolans. Thus, with the more consumption of HPCs, more attention has been paid to the shrinkage behavior of this concrete.

As well as SF, GGBS is a pozzolanic material which can be used as a cementitious ingredient in both cement and concrete composites. This supplementary material improves the performance characteristics of concrete, such as strength, workability, and volume change properties [Babu and kumar 2000]. Jianyong and Pei [1997] showed that GGBS improved long-term compressive strength of concrete. Generally, the early age strength of GGBS concretes is lower than the ordinary Portland cement concretes. However, when the curing period is extended, the strength increase was higher for the GGBS concretes. This is due to slow formation of CSH in the pozzolanic reaction.

It is well known that cracking due to shrinkage may produce a direct path for penetration of severe ions into concrete. To control this volume changes, application of GGBS to replace some parts of cement would be useful. Aly and Sanjayan [2008] showed that concretes contain GGBS exhibit an expansion in the curing period and consequently have smaller total shrinkage compared with plain concretes. Jianyong and Yan [2001] conducted extensive research on application of GGBS in HPC. They concluded that drying shrinkage is greatly reduced when GGBS is used as a replacement of cement. Similar results were observed by Saric-Coric and Aïtcin [2003]. Despite long-term advantages of GGBS, slowly reaction in the OPC/GGBS system decreases the amount of CSH at early ages. This leads to more immature microstructure at early ages than OPC/SF system. To improve both short-term and long-term performance of concrete, a ternary system (GGBS+SF) for substituting a part of cement would be useful. Some researchers [Saric-Coric and Aïtcin 2003] have studied influence of binary and ternary systems on long-term deformation of concretes. However, there are no long-term test data for the designated concrete mix design that is selected at the design stage. Thus, engineers require to predict long-term deformations of these systems for use in structures. In a number of papers on shrinkage prediction, comparisons between experimental results and prediction models have been presented [Mokarem et al. 2004; McDonald and Roper 1993; Ojdrovic and Zarghami 1996 and Karthikeyan et al. 2008]. To predict shrinkage of concrete, the engineer may consider various parameters such as: age and method of curing, relative humidity, type and content of aggregate and cement, slump, water and air content, compressive strength, geometry and shape of member and mineral or chemical admixtures used in concrete, but more complex shrinkage models, may not necessarily be more accurate than simple models [McDonald and Roper 1993]. Therefore, the comparison between prediction models and experimental results can be help to engineers for assessing the existing shrinkage prediction models and determine which model is more accurate than others to use.

In this research, the effects of pozzolanic materials on compressive strength and dimensional changes of HPCs are investigated. Four different mix designs were studied when some part of the cement was respectively replaced by SF, GGBS, and a ternary system (SF+GGBS). Then, for each of them, applicable shrinkage prediction models were assessed to determine which model is more appropriate.

EXPERIMENTAL INVESTIGATION AND METHODS

Materials

Table 1 shows chemical composition of used cement, GGBS, and SF, respectively. The coarse aggregate was gravel with the maximum particle size of 16mm, the fine aggregate was graded silica sand with fineness modulus of 3.2. For all mixtures, the water to binder ratio and total binder content were 0.38 and 420kg/m^3 , respectively.

Table1. Chemical Compositions (%) and Properties of Binding Materials

Binder	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	SO_3	Na_2O	K_2O	Specific gravity
Cement	21.00	5.00	63.00	1.800	3.500	1.60	0.50	0.60	3.15
GGBS	35.50	10.00	36.50	9.500	0.700	1.86	0.50	0.53	2.86
SF	93.16	1.13	-	1.60	0.72	0.05	-	-	2.11

Mix proportioning of HPCs

Four groups of HPC mixtures were designed. (A, B, C and D, have listed in Table 2). These four concrete mixtures made of the same mix proportioning except the type and the content of pozzolanic materials. Mixture A is plain concrete; In the Concrete B, silica fume replaced cement by 7.5% of cement weight; In Concrete C, GGBS replaced cement by 25% of cement weight while in Concrete D, 32.5% of cement was substituted by GGBS (25% of cement weight) and silica fume (7.5% of cement weight). The slump is almost the same for all mixtures.

Table2. Mix Proportioning

Concrete	Mix proportioning							Workability
	C*	GGBS	SF	SP	Coarse Aggregate	Fine Aggregate	W/C	Slump
	kg	kg	kg	%	kg	kg		cm
A	420	-	-	0.5	793	1000	0.38	14
B	390.5	-	29.5	0.6	793	988	0.38	15.5
C	315	105	-	0.5	793	992	0.38	18
D	285.5	105	29.5	0.5	793	980	0.38	15

* C = Cement

Specimens fabrication and testing

Compressive specimens were fabricated for each concrete mixture in accordance with ASTM C 192(98) and then were tested at 3, 7, 28 and 90 days according to ASTM C 39(98). Free shrinkage test was conducted according to ASTM C157 (98). The test method involves measuring the length change of 100mm×100mm×500mm concrete prisms. After fabricating, these specimens were covered with wet burlap for 24 hours; and then the specimens were removed from the steel molds. Initial measuring of the specimens was taken by a comparator regarding ASTM C490 (98). Figure 1 shows this test set up to measure variation of length of shrinkage specimens. After that, the specimens were placed in the curing water at 23Cº ± 1Cº for 6 days and length changes were measured every two days in the curing time. After this period, the specimens were removed and placed in a controlled environment of 25Cº ± 1Cº and 50% ± 2 RH. The length changes were measured up to 350 days subsequently.

Fig. 1. Unrestrained Shrinkage Measuring Setup

Applicable prediction models

Among the various varieties of methods proposed for the shrinkage prediction, eight of them are presented in this section. The following presents the equations for the eight applicable prediction models:

- **American Concrete Institute [ACI 209.2R-08 Code Model]:**

ACI proposed an empirical model for predicting the shrinkage strain as a function of time. Following equation presents the general model for predicting shrinkage strain.

Eq. (1)

where: = shrinkage strain (mm/mm); t= age of concrete (days); = age of concrete when drying starts at the end of moist curing (days); = duration of drying (days); *f*= the factor that depends on member shape and size of specimen; = ultimate shrinkage strain (mm/mm) depends on various parameters.

- **CEB MC90-99 model [CEB, 1999]:**

In this model, the new approach for shrinkage subdivides the total shrinkage into the components of autogenous shrinkage and drying shrinkage.

Eq. (2)

Eq. (3)

Eq. (4)

where: = total shrinkage strains of concrete, = autogenous shrinkage, = drying shrinkage at concrete age *t* (days) after the beginning of drying at (days), = the notional autogenous shrinkage coefficient, = the function describing the time development of autogenous shrinkage, = the notional drying shrinkage coefficient, = the coefficient for relative humidity of concrete and = the function describing the time development of drying shrinkage.

- **Bazant B3 model [Bazant 1995]:**

Equation (5) presents the general model for predicting the mean shrinkage strain :

Eq. (5)

where: = the ultimate shrinkage strain; = humidity dependence factor; = time curve, and = time from the end of the initial curing.

- **Huo et al. [Huo et al. 2001]:**

Huo et al. modified ACI equation by incorporating the strength correction factor. Modified equation can be used for HPCs for predicting shrinkage strain.

Eq. (6)

Where: = 28 days compressive strength (MPa).

- **Tadros [Tadros et al. 2003]:**

Tadros et al. proposed a simple and compact model for predicting the shrinkage strain:

Eq. (7)

where: *H*= relative humidity; = 28 days compressive strength (MPa); *V/S*= volume to surface area ratio (mm).

- **Caldarone [Caldarone 2009]:**

Caldarone proposed the following equation for predicting the shrinkage strain of high strength concrete:

Moist-cured concrete: = [t /(45 + t)]. Eq. (8)

Heat-cured concrete: = [t /(65 + t)]. Eq. (9)

where: = shrinkage strain (mm/mm); = *530* micro-strain.

- **Mazloom [Mazloom 2008]:**

Mazloom proposed some equations for estimating shrinkage of sealed and drying specimens that made by replacing some cement with silica-fume (SF) for high strength concretes.

Eq. (10)

For sealed specimens: Y= 0.014 * SF + 0.39
For drying specimens: Y= 1.14 - 0.007 * (V/S) $\geq$ 0.014 * SF + 0.39

where: SF= the percentage of silica fume replaced; *V/S*= volume to surface area ratio (mm).

- **Sakata [Sakata 1993]:**

Sakata proposed the following equation for shrinkage prediction:

Eq. (11)

Eq. (12)

where *H*= relative humidity; w= water content (kg/); *V/S*= volume to surface area ratio (mm).

RESULTS AND DISCUSIONS

Compressive strength

The experimental results of compressive strengths are listed in Table 3. As shown in this table, Concrete C acquired lower compressive strength than other concretes at early ages (3 days). In the later ages, this concrete shows much higher strength due to delay pozzolanic reaction of GGBS. It confirms this point from literature [Jianyong and Pei 1997] that GGBS concrete needs more than 3 day curing for strength development. Moreover, ACI 308 (98) suggests 7 days of moist curing for blended cement concrete. After 7 days of curing, Concrete B has the highest strength, followed by Concrete D, and A and C in turn. Up to the ages of 28 and 90 days, the reactivity of the SF and GGBS was developed greatly and consequently, all three blended concretes possessed greater compressive strength than Concrete A. Concrete C and D, especially, showed much higher strength values. It is worthwhile to note that after 28 days, Concrete A and B have no significant increase in compressive strength. Instead, Compressive strengths of Concrete C and D, which were blended with GGBS, significantly increased. Concrete D which was blended with combination of SF and GGBS has the highest compressive strength for 28 and 90 days. In the ternary system (Concrete D), compressive strength increased in the both short-term and long-term curing.

Table 3: Compressive Strength (Mpa) of Concrete

Age	Concrete A	Concrete B	Concrete C	Concrete D
3 days	35	37	29	33
7 days	40	51	40	44
28 days	51	59	58	70
90 days	51	59	63	74

Unrestrained Shrinkage

Figure 2 presents the average total shrinkage for unrestrained concrete specimens in drying room for about 28 days. After 6-days saturated curing, when all specimens subjected to drying condition, Concrete B exhibited a very rapid rate of shrinkage similar to that of the Concrete A in the early days of exposure. Pozzolanic materials like SF and GGBS typically increase the shrinkage. With adequate curing, pozzolans generally increase pore refinement, especially about SF. This could lead to the denser matrix produced by the SF and GGBS. It was found that shrinkage depends on loss of water from the mesopores (2-50nm) exist in C-S-H [Juenger and Jennings 2002] and also the size of macropores (50-10000nm) that determines how easily water may be lost from the mesopores [Young 1998]. The loss of this water produces stresses which cause the concrete to shrink [Neville 1998]. Aly and Sanjayan [2008] reported this denser matrix has smaller capillary voids, and the bulk of drying shrinkage in concrete occurs from the loss of water from the smaller capillary voids. In fact, capillary tensile force is the governing mechanism for early age shrinkage. Figure 2 demonstrate that Concrete D shrink quickly at early ages, with respect to Concrete C, but rate of shrinkage decreases after 5 days of exposure. Consequently, shrinkage of concrete D is lower than the concrete C after 28 days. In the one hand, using SF in the Concrete D causes more shrinkage than Concrete C at early ages but on the other hand, combination of SF and GGBS in the Concrete D shows less shrinkage than Concrete C in the long-term.

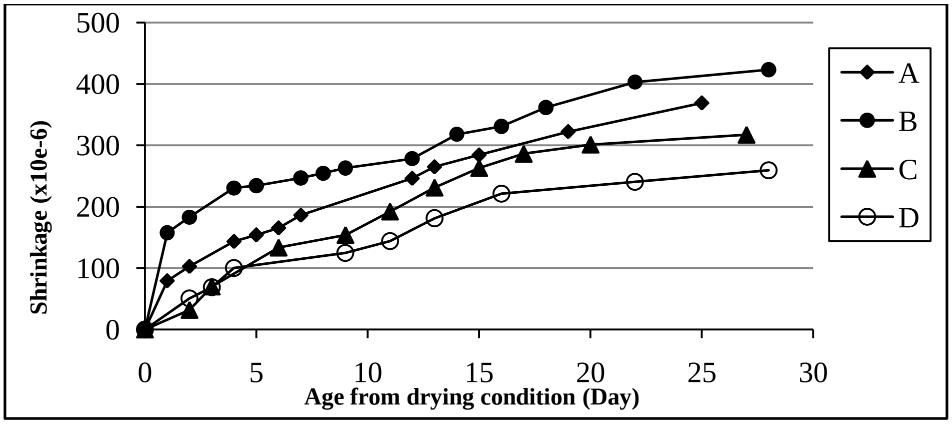

Fig. 2. Free Shrinkage (Short-Term Drying Condition) for All Mixtures

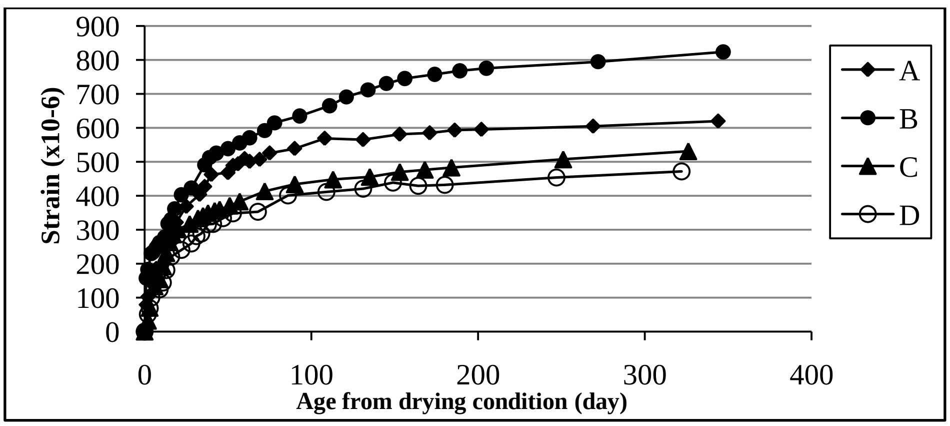

Fig. 3. Free Shrinkage (Long-Term Drying Condition) for All Mixtures

Prediction models

A residual value for each measured shrinkage specimen was calculated as follows:

Residual value= Predicted value – Measured value

A negative residual indicates that the model underestimates the experimental data, and a positive residual indicates that the model overestimates the experimental data. To determine which model is the best predictor, two analyses were performed: an error percentage analysis (EP) and the coefficient of variation (CV). The error percentage and coefficient of variation were calculated as follows:

EP= (Residual value*100)/Measured value Eq. (13)

Eq. (14)

where CV= coefficient of variation; J= experimental values; = Residual values at time t; n= number of variations.

In EP analysis, the model with minimum average error percentage is the best predictor and the best model for the CV test, is model with minimum value. Figures 4 to 7 show the comparisons of predictions of various conventional models for shrinkage strain with respect to the experimental results developed in this study. It is noted that, the ACI 209, Huo and Sakata models are applicable for only type I general and type III high early strength cements, thus residuals were not calculated for the mixtures containing slag for the ACI 209, Huo and Sakata models, because these cementing materials are closer in hydration characteristics to type II cement rather than type I or III.

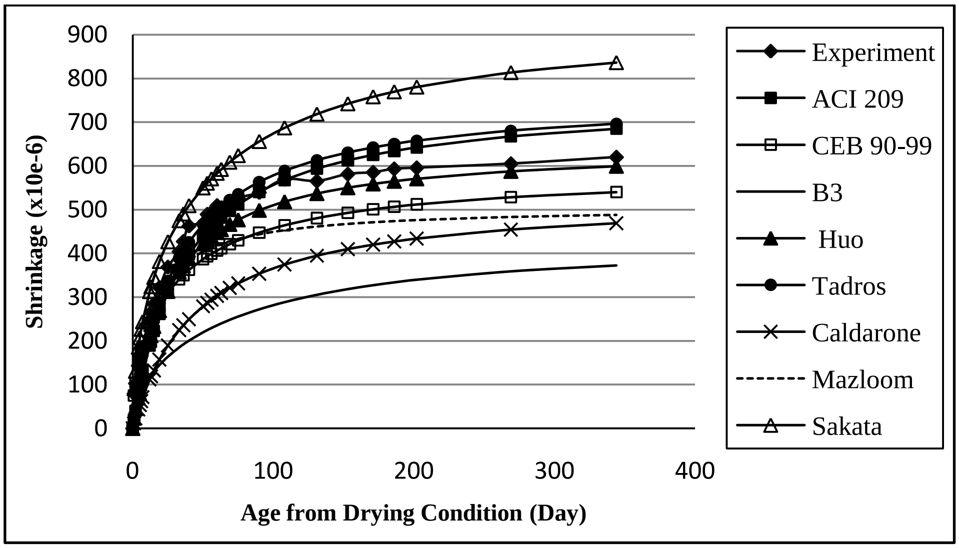

Fig4. Experimental Data and Calculated Values for Mix Design A

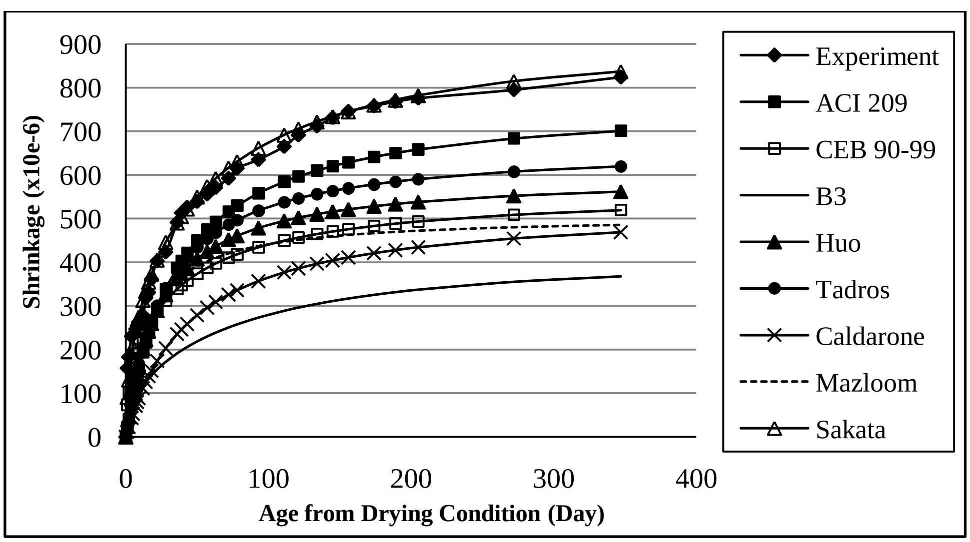

Fig5. Experimental Data and Calculated Values for Mix Design B

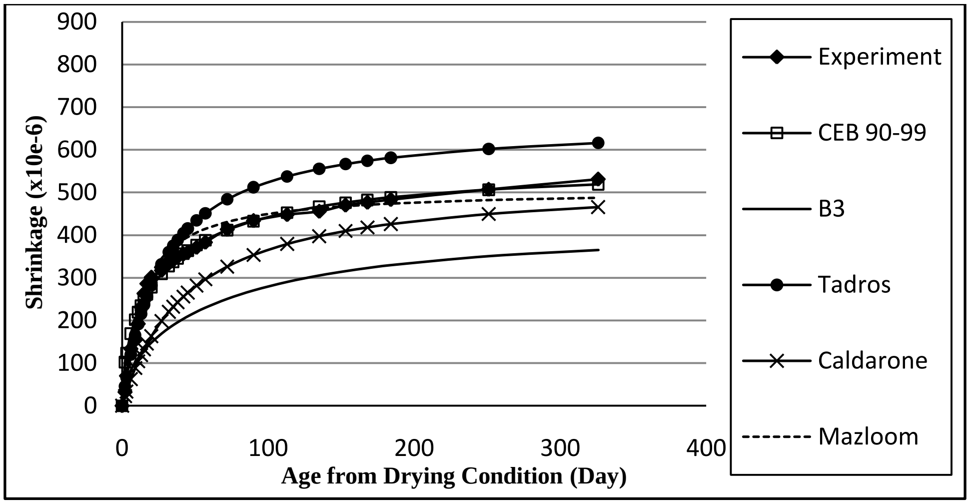

Fig6. Experimental Data and Calculated Values for Mix Design C

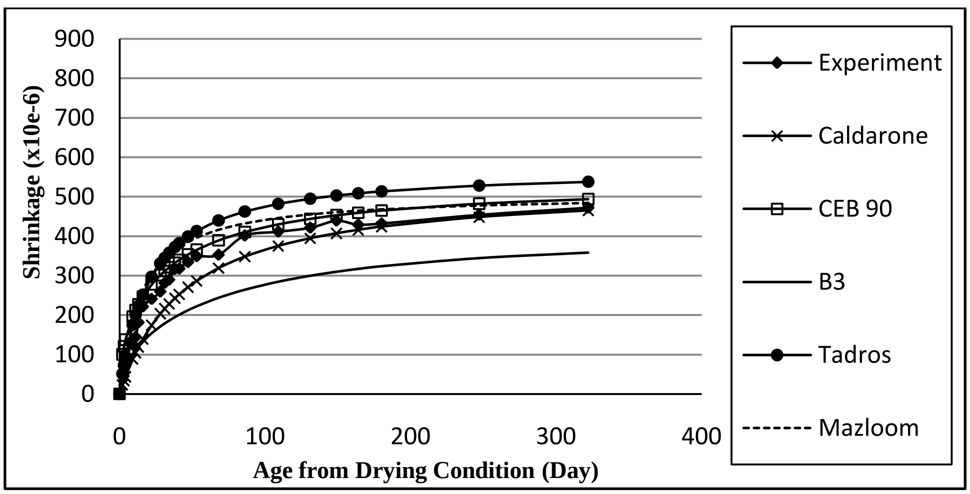

Fig7. Experimental Data and Calculated Values for Mix Design D

Tables 4 and 5 present the summary of models average error percentage and coefficient of variation for the four mix designs. For plain concrete A, based on the EP analyses and CV test, the Tadros model was the best predictor of shrinkage, although it was underestimated the shrinkage. This model also showed the good results for shrinkage prediction of concrete C.

Generally, the Sakata model shows higher shrinkage values as a time with respect to other models, on the other hand, using SF leads to increment of shrinkage in concrete. Thus, as seen in the results, precise model for shrinkage prediction of concrete mix design B, is the Sakata model. This model is so simple to use and it can be shown that more complex shrinkage models may not necessarily be more accurate than simple models. This is in agreement with the finding of others [McDonald and Roper 1993]. Although the Mazloom model is proposed for HPCs containing SF, but based on the results of this study, this model exhibited better results for HPCs containing GGBS (concrete mix designs C and D) with respect to SF. For concrete C, based on the EP analyses, the Tadros model was the best predictor of shrinkage and based on the CV test, the CEB model was more appropriate than others. For concrete D, based on the EP analyses, the Mazloom model was the best predictor of shrinkage and based on the CV test, the CEB model was better than others. The ACI and Huo models showed the same results for concretes A and B. The results of these models were acceptable for plain concrete A, only and the results of the ACI model were better than Huo model. The Caldarone model showed acceptable results for shrinkage prediction of HPCs in long-term and it seems that, with increment of the concrete strength, the results of this model improve. The B3 model exhibited poor and non-conservative results for shrinkage prediction of HPCs, although, this models is almost complex. Based on the results of this study, the accuracy of shrinkage prediction models depends on the pozzolans used in the specimens. Thus, the effects of pozzolans such as silica fume, slag, metakaolin and other natural pozzolans should be consider in the shrinkage prediction models.

Table4. Results of the Error Percentage Analyses

Mix Design	Prediction Models							
	ACI 209	CEB 99	B3	Huo	Tadros	Caldarone	Mazloom	Sakata
A	-13.75	-12.24	-50.6	-16.74	-8.45	-45.56	-15.32	23.24
B	-27.59	-32.14	-60.49	-33.78	-29.76	-54.99	-34.34	-1
C	-	13.55	-35.56	-	-10.39	-30.01	12.48	-
D	-	19.92	-29.44	-	18.58	-21.66	-18.26	-

Table5: Results of the Coefficient of Variation Analyses

Mix Design	Prediction Models							
	ACI 209	CEB 99	B3	Huo	Tadros	Caldarone	Mazloom	Sakata
A	0.12	0.178	0.54	0.12	0.1	0.41	0.19	0.27
B	0.22	0.37	0.64	0.32	0.27	0.52	0.38	0.05
C	-	0.07	0.42	-	0.18	0.28	0.086	-
D	-	0.13	0.37	-	0.23	0.18	0.18	-

CONCLUSIONS:

- Concrete containing GGBS is highly influenced by the type of curing regime used at early ages. Curing for more than 3 days is necessary for the strength development of GGBS concrete. In fact, extending the curing time in concrete containing GGBS has a positive effect on increasing of compressive strength in later ages. When SF and GGBS were simultaneously used in concrete, positive synergistic effect on increasing compressive strength is in the both early and later ages.
- The shrinkage strain of GGBS concrete in short-term and long-term is considerably less (40%) than the shrinkage strain of plain and SF concretes. Similar effect was observed for long-term when combination of SF and GGBS was used to make blended concrete.
- The accuracy of shrinkage prediction models depends on the pozzolans used in the specimens and more complex shrinkage models may not necessarily be more accurate than simple models.

- To determine which model is the best predictor, an error percentage analysis (EP) and the coefficient of variation test (CV) were performed. For concretes A and B, the Tadros and Sakata models were the best, respectively. According to the EP analysis, the Tadros model was the best predictor of shrinkage and based on the CV test, the CEB model was better than others for concrete mix design C. For concrete mix design D, based on the EP analyses, the Mazloom model was the best predictor of shrinkage and based on the CV test, the CEB model was more appropriate than others.
- Based on the results of this study, it seems that the effects of pozzolans such as silica fume, slag, metakaolin and other natural pozzolans should be consider in the prediction models.

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