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# Effect of high volume fly ash on shrinkage of self-compacting concrete

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**Abstract**

Self-compacting concrete (SCC) has been produced incorporating fly ash as cement replacement at 35%, 55% and 65% by weight. The flowability, fillingability and passingability of these concrete were assessed by combination of the following test methods: flow table, J-Ring, L-Box, Box Type and V-funnel test. For each mix proportion of SCC, six cylinder specimens (75 mm x 275 mm) were cast for shrinkage measurements following the RILEM Recomendation. Three of them were used for measurement of drying shrinkage while the other three were used for autogenous shrinkage. The results show that a higher cement replacement by fly ash tends to decrease both drying and autogenous shrinkage. Estimations of shrinkage using ACI 209R, CEB-FIP 1990 and Ross's method suggest that ACI 209R and CEB-FIP 1990 provide accurate prediction than Ross's model.


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*Keywords:* autogenous shrinkage; drying shrinkage; fly ash; self-compacting concrete

## 1. Introduction

Self-compacting concrete (SCC) is a type of concrete which can be placed and compacted under its own weight with little or no vibration. The important fresh properties that characterize SCC are fillingability, passingability and segregation resistance [1]. A combination of test methods has been proposed to specify these fresh properties:flow table, J-Ring, L-Box, Box Type and V-funnel test [2].To achieve such properties, Okamura and Ozawa [3] suggested

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the following guidelines: the volume of coarse aggregate is limited to 50% of the total solid volume; fine aggregate used is no more than 40% of the total mortar volume; volume ratio of water/binder is in the range of 0.9-1; and finally the superplasticizer dosage is determined to meet the self-compacting criteria. If no other powder material is used except that of cement, the proportion will usually require a high cement content.

**Nomenclature**

| | |
|---|---|
| $\beta s$ | coefficient of shrinkage dev. CEB-FIP 1990 model |
| $\varepsilon_{sh(t)}$ | shrinkage at time t |
| $\varepsilon_{sh(u)}$ | ultimate shrinkage |
| $\varepsilon_{sh(28)}$ | shrinkage at 28 days |
| $\varepsilon_{sh(t)-p}$ | predicted shrinkage at time t |
| $\varepsilon_{sh(t)-m}$ | measured shrinkage at time t |
| $\varepsilon_{sh(t)-pr}$ | average predicted shrinkage from the beginning until time t |
| n | number of shrinkage data points |
| $t_{200}$ | time of SCC to flow and reach 200 mm in L-Box test |
| $t_{400}$ | time to SCC to flow and reach 400 mm in L-Box test |
| $t_{500}$ | time of SCC to spread and reach 500 mm in Flow table and J-Ring test |
| u | perimeter of cross-section |

Having a high cement content in the production of SCC, there is a disadvantage with regard to the shrinkage of this type of concrete. Shrinkage is a volumetric contraction of concrete caused by evaporation or hydration of cement. When concrete is already in hardened state a withdrawal of capillary water due to evaporation will result in drying shrinkage. Meanwhile, if evaporation is prevented concrete can be nevertheless loss of its capillary water due to self-dessication i.e. consumption of capillary water in the progress of hydration. The volumetric contraction as a result of self-dessication is termed autogenous shrinkage [4,5]. Both type of shrinkages are originated in cement paste while aggregates in concrete act to restrain these volumetric contractions. Since the proportion of aggregate and cement in SCC are relatively low and high, respectively, these factors tend to promote a higher shrinkage of SCC compared to normal concrete [6].

Reduction of cement content in SCC is possible by partial replacement of cement with fly ash. The spherical shape and finer size of fly ash could be beneficial to enhance fillingability and passingability of SCC while maintaining segregation resistance. Various investigators [7-10] utilized fly ash at high volume replacement levels in SCC for a variety purpose. With respect to shrinkage, the use of fly ash tends to reduce both drying and autogenous shrinkage. Thus, it is expected that incorporating high volume fly ash in SCC will prevent the occurence of long-term shrinkage related problems.

Assessing the potential long-term shrinkage related problems will require a quantification of long-term magnitude of shrinkage especially its ultimate value. However, it is impossible to obtain the ultimate value by direct measurement of shrinkage in the laboratory. Most of the codes suggest that a laboratory measurement of shrinkage is carried out at a very limited time (90 days). Hence, a model to estimate long-term shrinkage is necessary. There are several models available for this purpose i.e. ACI 209R [11] and CEB-FIB 1990 [12] method. Both methods are derived for estimating long-term shrinkage of normal concrete. However, Pernandez-Gomez and Landsberger [13] confirmed that both methods are applicable for SCC. Another method is specifically applies for estimating autogenous shrinkage based on Ross's hyperbolic equation. Eqs 1-5 summarize the models where all the notations have been given in the Nomenclature.

- ACI 209R

$$\varepsilon_{sh(t)} = \frac{t}{35+t}\varepsilon_{sh(u)} \tag{1}$$

- CEB-FIP 1990

$$\varepsilon_{sh(t)} = \varepsilon_{sh(u)}\beta_s \tag{2}$$

$$\beta_s = \sqrt{\frac{t}{350(\frac{h}{100})^2 + t}} \quad (3)$$

$$h = \frac{A_c}{u} \quad (4)$$

- Ross's Model

$$\varepsilon_{sh(t)} = \frac{t}{57.4 + t} 2.3575 \varepsilon_{sh(28)} \quad (5)$$

Three methods may be applied to evaluate the acurracy of shrinkage prediction models i.e. best-fit line, residual analysis (R) and coefficient of variation of error (COV). Best-fit line is a method to correlate the magnitude of shrinkage prediction and measurement by regression analysis. Value of R is calculated from the difference between shrinkage predictionand measurement. If the difference is positive, the model tends to overestimate shrinkage and vice versa. Meanwhile, COV is calculated using Eq. 6 in which subscripts *pr*, *p* and *m* represent average prediction, prediction and measurement of shrinkage after time *t,* respectively, with *n* number points of shrinkage data.

$$COV = \frac{1}{\varepsilon_{sh(t)-pr}} \sum_{i=0}^{t} [\frac{(\varepsilon_{sh(t)-p} - \varepsilon_{sh(t)-m})^2}{n}]^{1/2} \quad (6)$$

## 2. Experimental Works

### *2.1. Proportion of SCC*

The proportion of materials for producing three mixes of SCC is given in Table 1. Three concrete mixes are identified as SCC-35%, SCC-55% and SCC-65% in which the percentages are representation of the amount of fly ash. These percentages of fly ash are calculated on the basis of the total weight of cement plus fly ash (binder).The amount of fine aggregate (sand), coarse aggregate, superlasticizer and binder are identical for all three mixes but the water requirement in each mix is judged to obtain similar target of flowability. The maximum aggregate size used in these mixes is 10 mm.

### *2.2. Fresh Properties of SCC*

The following test methods were carried out to assess the fresh characteristics of SCC i.e. flow table, J-Ring, L-Box, Box-Type and V-funnel test. These test methods followed reference [2]. Table 2 shows the fresh properties of SCC used in this study. All three mixes meet the requirements of SCC.

Table 1. Mix proportion of SCC

| Mix Identification | Cement (kg) | Fly ash (kg) | Sand (kg) | Coarse Aggregate (kg) | Water (kg) | Superplasticizer (kg) |
|---|---|---|---|---|---|---|
| SCC-35% | 440 | 237 | 671 | 670 | 151 | 7.72 |
| SCC-55% | 305 | 373 | 671 | 670 | 149 | 7.72 |
| SCC-65% | 237 | 440 | 671 | 670 | 124 | 7.72 |

Table 2. Fresh properties of SCC

| Type of test | Parameter | Results | | |
|---|---|---|---|---|
| | | SCC-35% | SCC-55% | SCC-65% |
| Flow Table | diameter (mm) | 745 | 740 | 765 |
| | t500 (sec) | 3.70 | 3.57 | 3.27 |
| | velocity (mm/sec) | 32.53 | 37.46 | 54.26 |
| J-Ring | diameter (mm) | 605 | 680 | 665 |
| | t500 (sec) | 9.58 | 8.36 | 7,15 |
| | velocity (mm/sec) | 17.96 | 35.38 | 35.40 |
| L-Box Type | t200 (sec) | 3.34 | 4.20 | 5.40 |
| | t400 (sec) | 6.50 | 6.70 | 7.20 |
| | h2/h1 | 0.73 | 0.90 | 0,85 |
| Box Type | h2 (mm) | 350 | 350 | 350 |
| | h2/h1 | 1 | 1 | 1 |
| V funnel | t (sec) | 24.73 | 22.98 | 16.00 |

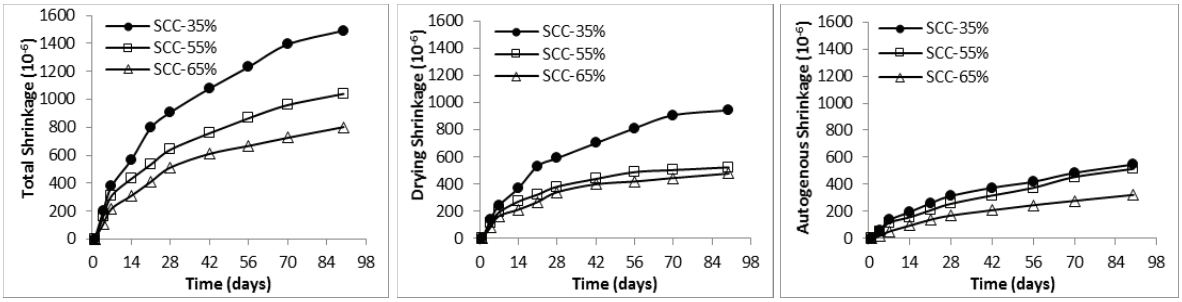
Fig.1. Unsealed and sealed specimens (left) and measurement of length change using Demec Gauge (right)

### *2.3. Measurement of shrinkage*

Six cylinder specimens of 7.5 mm x 275 mm were cast for each mix proportion of SCC. The shape and size of specimen followed the RILEM Recommendation [14]. Three cylinders were used for drying shrinkage measurement and another three cylinders were prepared for autogenous shrinkage measurement. To prevent evaporation in the autogenous shrinkage specimens, the cylinders were wrapped with aluminium foil tape. The sealing of the cylinders with aluminium foil tape was carried out at 1 day after casting. No loss of capillary water due to evaporation on sealed specimens could be justified from the steady weight of these specimens while evaporation on drying (unsealed) specimens were noted from continues reduction of specimens weight with time. On each surface of cylinder specimen (either sealed or unsealed cylinder), 4 pairs of demec points with gauge lengths of 200 mm at equidistant of 90$^{o}$ were glued using epoxy adhesive. All the gluing process of demec points were conducted at 1 day after casting with special note that for sealed specimens the process was carried out after the sealing of specimens finished. The change in length of the cylinder specimen was measured using Demountable Mechanical Strain Gauge (Demec Gauge) on all four pairs of demec points. Thus, for each cylinder specimen the change in length due to shrinkage was taken as an average of four readings. The Demec Gauge has a resolution of 1 micron. The measurement of a change in length of the cylinder specimen was conducted at the age of 1, 4, 7, 14, 21, 28, 42, 56, 70 and 90 days. The magnitude of shrinkage was then calculated by dividing the change in length with the original (gauge) length of 200 mm. Fig. 1 shows two type of specimens (unsealed and sealed) and measurement of length change using Demec Gauge. The laboratory environments during shrinkage tests were monitored continuously. It was noted that the temperature and humidity was, respectively, in the range of 25-32ºC and 70-80%.

## 3. Results and Discussion

### *3.1. Shrinkage behaviour of SCC with high volume fly ash*




(a) (b) (c)

Fig. 2. The results of shrinkage observed on unsealed specimens (a) and sealed specimens (c). The drying shrinkage (b) is calculated by deducing the total shrinkage of unsealed specimens with autogenous shrinkage of sealed specimens

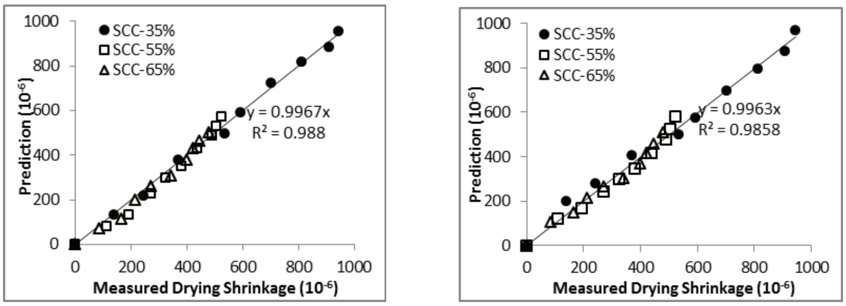
The loss of capillary water that causes reduction in length on an unsealed specimen is due to both evaporation and self-desiccation. Hence, the shrinkage measured on unsealed specimen is termed as total shrinkage. Meanwhile, the autogenous shrinkage measured on sealed specimen is triggered by self-desiccation only. To obtain drying shrinkage caused by evaporation, the magnitude of total shrinkage obtained on unsealed specimen must be deduced by autogenous shrinkage. Fig. 2 shows total shrinkage, drying shrinkage and autogenous shrinkage of SCC at various fly ash contents. Shrinkage tends to increase at a higher rate at the beginning of time and then the rate is diminished at later age. SCC with a higher fly ash content is likely to cause a reduction in the magnitude of both drying and autogenous shrinkage. The magnitude of drying shrinkage is higher than that of autogenous shrinkage indicating volumetric contraction of SCC investigated in this study is dominated by evaporation mechanism. However, it is obvious that the magnitudes of drying shrinkage are likely to increase at a lower rate than those of autogenous shrinkage after 90 days. Hence, at later age it seems that an increase in the magnitude of shrinkage may be dominated by autogenous shrinkage.

There are several factors which must be considered to explain the shrinkage behaviour of SCC observed in his study. These are cement content, water content and pore refinement due to pozzolanic reaction of fly ash. It is known that cement paste is the source of shrinkage in the concrete. Consequently, SCC with a higher cement content will produce a higher shrinkage and vice versa. The results of this study is consistent with this account where SCC with a lower fly ash as cement replacement shows a higher shrinkage. The loss of capillary water due to evaporation is controlled by the size of interconnected-pores in the concrete which act as channel of moisture to flow. More capillary water will easily move out to the drying environment through the higher size of interconnected-pores. At early age the pozzolanic reaction is not yet taken place and so the pore characteristics of the SCC is governed by the water content in the mix. Therefore, at early age drying shrinkage triggered by evaporation mechanism is the dominant factor. SCC-35% is proportioned to have a higher water content than the others; it is not surprising that the drying shrinkage of this concrete is the greatest. At later age, the pozzolanic reaction will reduce the pores size of concrete. At the same time the evaporation has reduced the humidity of the concrete to reach a state of balance with the environment where in this study the laboratory environment (humidity) is set to about 70-80%. In turn, the depletion of capillary water which causes shrinkage is now dominated by self-desiccation.

### *3.2. Prediction of shrinkage*

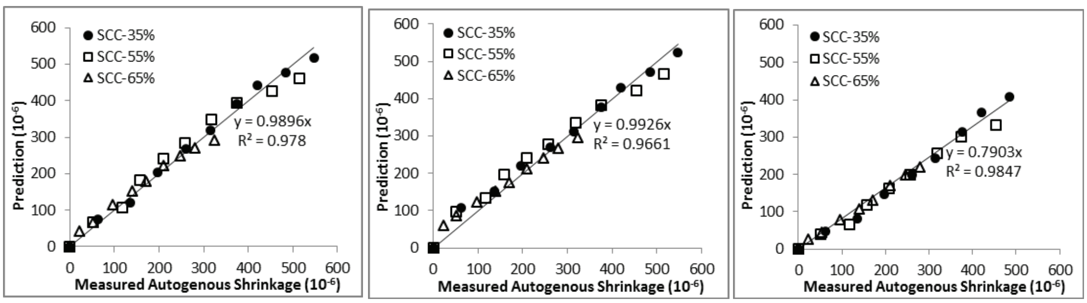
Three methods of shrinkage prediction are applied in this study i.e. ACI 209R, CEB-FIP 1990 and Ross's method. Both ACI 209R and CEB-FIP 1990 method require that the ultimate shrinkage has to be determined first so that the long-term shrinkage at any time may be estimated. While for Ross's method it is autogenous shrinkage at 28 day that has to be determined first. Given the ACI 209R and CEB-FIP 1990 model as those of Eq. 1 and 2, the ultimate shrinkage, $\varepsilon_{sh(u)}$ , can be obtained by the following procedure. First, the shrinkage data, $\varepsilon_{sh(t)}$, observed from the laboratory are plotted in Y-axis while the corresponding parameters (t/35+t) and $\beta_s$ are plotted in X-axis for ACI 209R and CEB-FIP 1990 model, respectively. Then, a linier regression analysis is performed on each of these graphs in which the linier lines of regression should cross 0.0 axes. The gradient (m) of these lines correspond to ultimate shrinkage,$\varepsilon_{sh(u)}$ for ACI 209R and CEB-FIP 1990 model. Similar procedure can be executed for Ross's model but instead of ultimate shrinkage it is the value of autogenous shrinkage at 28 day, $\varepsilon_{sh(28)}$, that will be obtained. These values will then be used to estimate shrinkage of all SCC using Eq. 1, 2 and 5 at corresponding times of shrinkage measurement. In this way, comparison of predicted and measured shrinkage could be evaluated to determine the accuracy of the models.

Fig. 3 and 4 show comparison between prediction vs. measurement values of drying shrinkage and autogenous shrinkage, respectively. Equality between these shrinkage prediction values and the corresponding shrinkage measurements is evaluated using best-fit line method. The resulted linier regression lines indicate that all the methods provide good equality between predicted and measured shrinkage as the gradients (m) of these lines are closed to 1 with the exception of Ross's model for autogenous shrinkage prediction. The Ross's model tends to overestimate autogenous shrinkage values by 20%. The correlations between predicted and measured shrinkage ($R^2$ values) indicates that the data are well grouped about the regression lines. The values of m and $R^2$ are summarized in Table 3.



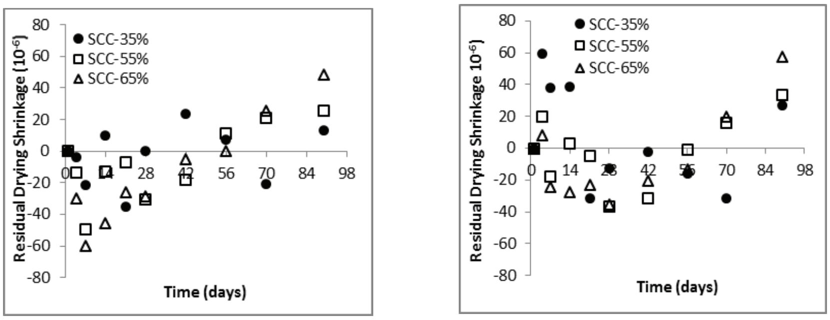

(a) ACI 209R (b) CEB-FIP 1990

Fig. 3. Prediction vs. measurement of drying shrinkage and evaluation of the prediction's accuracy using best-fit line method



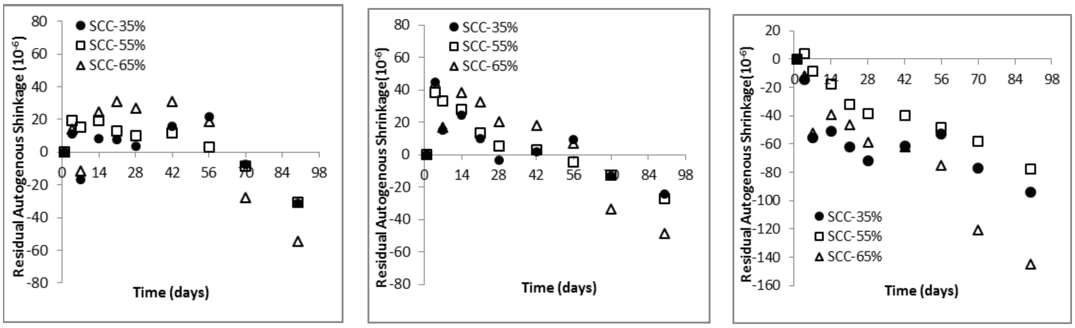

(a) ACI 209R (b) CEB-FIP 1990 (c) Ross's model

Fig. 4. Prediction vs. measurement of autogenous shrinkage and evaluation of the prediction's accuracy using best-fit line method




(a) ACI 209R (b) CEB-FIP 1990

Fig. 5.Plots of residual values of drying shrinkage prediction methods




(a) ACI 209R (b) CEB-FIP 1990 (c) Ross's model

Fig. 6.Plots of residual values of autogenous shrinkage prediction methods

Residual values (R) calculated from the difference between predicted and measured shrinkage are plotted in Fig. 5 and 6 for drying and autogenous shrinkage, respectively. At the beginning of time, the R values are negative indicating both ACI 209R and CEB-FIP model tend to underestimate the drying shrinkage, but after about 42 days the R values turn to be positive suggesting the models start to overestimate the drying shrinkage (see Fig. 5). Based on the average values of R calculated up to 90 days of drying shrinkage, it is found that the R values of both methods tend to be negative with CEB-FIP 1990 gives a lesser R (see Table 3). The maximum value of R is less than 60 x $10^{-6}$ for both methods with the average values of R less than 10 x $10^{-6}$. These values are less than those observed by Fernandez-Gomez and Landsberger [13] suggesting that both methods provide an acceptable accuracy. For autogenous shrinkage prediction, the trends are in contrast to those of drying shrinkage. Fig. 6 suggests that at the beginning of time, the R values are positive and then turns to be negative after about 56 days for autogenous shrinkage prediction using ACI 209R and CEB-FIP 1990. While for Ross's model, the R values are continuously negative from the beginning. The average values of R are positive for autogenous shrinkage prediction using ACI 209R and CEB-FIP 1990 but negative for Ross's model. It is also confirmed that Ross's model is the least accurate model for autogenous shrinkage prediction as this model gives the highest R (see Table 3).

Coefficient of variation of errors (COV) calculated using Eq. 6 for all the shrinkage prediction models are summarized in Table 3. Both ACI 209R and CEB-FIP 1990 gives almost similar values of COV either for predicted drying shrinkage or autogenous shrinkage. Both methods tend to give a better prediction when they are applied for drying shrinkage compared to autogenous shrinkage. Meanwhile, Ross's model is the least accurate method to estimate autogenous shrinkage as judged by the highest value of COV.

Table 3. Accuracy of various shrinkage prediction methods

| **Shrinkage Data** | **Accuracy of shrinkage prediction method** | | |
|---|---|---|---|
| | **ACI 209R-92** | **CEB-FIP 1990** | **Ross** |
| | | **Best-fit line – m and $R^2$** | |
| Drying | m = 0.9967; $R^2$ = 0.989 | m = 0.9963; $R^2$ = 0.978 | NA |
| Autogenous | m = 0.9896 ; $R^2$ = 0.986 | m = 0.9926; $R^2$ = 0.966 | m = 0.7903; $R^2$ = 0.985 |
| | | **Residual Analysis -Average of R ($10^{-6}$)** | |
| Drying | -7.341 | -0.382 | NA |
| Autogenous | 3.963 | 8.300 | -48.897 |
| | | **Coefficient of variation of error- COV (%)** | |
| Drying | 18.555 | 18.857 | NA |
| Autogenous | 23.408 | 26.956 | 88.057 |

## 4. Conclusions

This study suggests the following conclusions:

- SCC with a higher fly ash content as cement replacement tend to reduce both drying and autogenous shrinkage. Several factors contribute to this reduction which may include cement content, water content and pore sizes refinement.
- Both ACI 209R and CEB-FIP 1990 may be applied to estimate both drying shrinkage and autogenous shrinkage. These methods give similar and acceptable accuracy when assessed using best-fit line, residual analysis and coefficient of variation of error. While it is not suggested to use Ross's model to estimate autogenous shrinkage as this model give an inaccurate prediction.

## References

[1] S. Tangtermsirikul and K. Khayat, Part III: Fresh concrete properties, in A. Skarendahl, O. Petersson (Eds), Self-compacting concrete, State of the Art Report of RILEM Technical Committee; 2000, pp. 17-22.
[2] K. Takada and S. Tangtermsirikul, Part IV: Testing of fresh concrete, in A. Skarendahl, O. Petersson (Eds), Self-compacting concrete, State of the Art Report of RILEM Technical Committee; 2000, pp. 25-39.
[3] H. Okamura and K. Ozawa, Mix design for self-compacting concrete, Concrete Library of JSCE 25 (1995), pp. 107-120.
[4] A. Alfirai, S. Aggoun, A. Kadri, S. Kenai and E. Kadri, Pastes and mortars studies on the influence of mix design parameters on autogenous shrinkage of self-compacting concrete, Construction and Building Materials 47 (2013), pp. 969-976.
[5] M.J. Oliveira, A.B. Ribeiro and F.G. Branco, Combined effect of expansive and shrinkage reducing admixtures to control autogenous shrinkage in self-compacting concrete, Construction and Building Materials 52 (2014), pp. 267-275.
[6] A. Leeman, P. Lura and R. Loser, Shrinkage and creep of SCC- the influence of paste volume and binder composition, Construction and Building Materials 25 (2011), pp. 2283-2289.
[7] E. Guneyisi, M. Gesoglu and E. Ozbay, Strength and drying shrinkage properties of self-compacting concretes incorporating multi-system of blended mineral admixtures, , Construction and Building Materials 24 (2010), pp. 1878-1887.
[8] I. Pappayiani and E. Anastasiou, Development of self-compacting concrete by using high volume calcareous fly ash, World of Coal Ash Conference, Denver, USA, 2011.
[9] M. Liu, Self-compacting concrete with different levels of pulverized fuel ash, Construction and Building Materials 24 (2010), pp. 1245-1252.
[10] Sunarmasto and S.A. Kristiawan, Effect of fly ash on compressive strength and porosity of self-compacting concrete, Applied Mechanics and Materials 754-755 (2015), pp. 447-451.
[11] ACI Committee 209, Prediction of creep, shrinkage and temperature effect on concrete structures (ACI 209R-92), American Concrete Institute, Farmington Hill, MI, 1992.
[12] CEB-FIP 1990, Model code for concrete structures, Bulletin d'Information 199, 1991.
[13] J. Fernandez-Gomez and G.A. Landsberger, Evaluation of shrinkage prediction models for self-compacting concrete, ACI Materials Journal 104 (2007), pp. 464-473.
[14] RILEM TC 107 Recommendation, Measurements of time-dependent strains of concrete, Materials and Structures 31 (1998), pp. 507-512.