Moisture transport in self compacting concrete: a combined experimental-finite element approach

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ABSTRACT: The self compacting concrete (SCC) is now being extensively used in major projects worldwide. This high performance new generation concrete flows freely through congested reinforcement in concrete without any compaction and vibration. Moisture diffusion and associated shrinkage in restrained concrete members generates cracks, which in the arid and harsh environment of Gulf region, results in corrosion of reinforcement and cracking and/or delamination of concrete. This paper addresses the moisture transport in SCC under two exposure conditions representing normal and extreme ambient environment. Non-linear finite element analysis in conjunction with drying tests is used to compute diffusivity of SCC and assess the influence of high temperature and wind on moisture diffusivity and convective moisture transfer coefficient of SCC. Drying and shrinkage tests were conducted on two types of SCC, one based on high range water reducing admixture and dispersing agent and the other based on polycarboxylic ether-based plasticizer, and results are compared with silica fume concrete. Moisture diffusion and shrinkage was found to be significantly higher in SCC as compared to silica fume concrete.

1 INTRODUCTION

Deterioration of concrete structures in a short span of time due to corrosion of reinforcing steel and the associated cracking and delamination of the concrete cover is widespread in the Arabian Gulf region. This can be attributed to the harsh ambient climate characterized by high temperature and ambient salinity, with humidity regime traversing from very low to high values and high winds in summer. Furthermore, the lack of adequate quality control in concrete construction in the region results in low strength and high permeability concrete with voids and honeycombing especially near congested reinforcing, which exacerbates the problem of rapid deterioration of concrete structures. In order to combat the alarming rate of concrete deterioration in the region, the major thrust has been towards usage of dense concrete, such as silica fume concrete, to block the pathways for the ingress of chlorides and sulfates into the concrete element. The advancement of innovative self compacting concrete in the recent years and its induction in the market in Japan and Europe can be considered as the first major revolution in concrete industry over the past several decades. The development of self compacting concrete was first reported in 1989 by Ozawa et al. (1989). Enormous growth has taken place ever since in Japan and several major structures have been built using this concrete. Self compacting concrete was adopted by Europe in the late 1990s and by United States in early 2000. Self compacting concretes offers new possibilities and scenarios in regard to economy and durability of the structures (Collepardi 2003). Due to its specific properties, these concretes may contribute to a significant improvement of the quality of concrete structures and open up new fields for the application of concrete (Holschemacher & Klug 2002).

Self Compacting Concrete (SCC), also known as super workable concrete or self consolidating concrete or self flowing concrete is a semi-liquid high performance concrete characterized by high resistance to segregation and bleeding and has low yield value which imparts high flowability to concrete. It can flow easily into congested reinforcing steel and tight corners in complex structural element without any compaction and vibration. The composition of SCC is same as that of normal concrete but to attain the self compactability and enhanced durability performance, admixtures such as fly ash, silica fume, glass filler, limestone powder, quartzite etc. are used. The main ingredient which imparts fluidity to the SCC comes from the new generation super plasticizers such as polycarboxylate polymer technology based high range water reducing admixtures and dispersing agents. Another type of self compacting concrete called Enhanced Self Compacting Concrete (ESCC) is obtained by adding only polycarboxylic ether polymer based plasticizer to the normal concrete. The polycarboxylic ether polymer works on nano-technology, which makes it possible to start the molecular interactions between polymers and cement to build up the desired performance in concrete, so there is no need for adding admixtures.

The elimination of mechanical voids and un-intentional air voids in the concrete mass, removal of unnecessary water, shaking the particles in the mix into their closest nesting, providing uniform dispersal and distribution of the large particles, but still retaining the coating of all particle surfaces with cement mortar, which is achieved by vibration in normal concrete is achieved in auto-mode in the self compacting concrete (Welton 1987). Physical shortcomings in normal concrete such as reduced bond strength to reinforcement and settlement cracks around the rebars are eliminated without vibration. (Forssblad 1987). In the aggressive environment which exists in the Gulf region, self compacting concrete could alleviate the problem of rampant corrosion of steel in concrete and its cracking and delamination.

The diffusion of moisture from the concrete is a key physical process, which generates several physical mechanisms, drying shrinkage being the principal one. Moisture diffusion in the domain of the concrete element and its egression from the surface due to the moisture gradient between the exposed layers of concrete and the ambient humidity causes shrinkage deformations and results in the development of flaws in the concrete matrix and cracking in the concrete cover concrete. These flaws and cracks provide potential pathways for ingress of aggressive species such as chlorides from the external environment. The self compacting concrete in general has high volume of fines to achieve the flowability which could diminish the restraint to deformation provided by larger aggregates, resulting in higher shrinkage. On the other hand, the dense matrix with reduced flaws, minimal voids and other characteristics imparted by fluidity of self compacting concrete could inhibit moisture transmission to the ambience and reduce the shrinkage deformation at early ages. In-depth study of moisture transport characteristics and drying shrinkage of self compacting concrete is therefore of high importance to ascertain the viability of this "concrete of future" in the aggressive environment of Gulf region.

Only a few studies have been conducted on moisture transport and shrinkage in self compacting concrete, with conflicting results reporting either a substantial enhancement of drying shrinkage or a significant reduction of the same. Kim et al. (1998) have reported that the drying shrinkage of self compacting concrete was 30 to 50% more than normal concrete. Ozyildirim & Lane (2003) found drying shrinkage of self compacting concrete investigated at below 400 $\mu\varepsilon$ at 28 days and 700 $\mu\varepsilon$ at 4 months. Xie et al. (2002) have reported that less water did not permeate in the self compacting concrete, with an average permeability height of 15 mm under a pressure 2.5 MPa. The drying shrinkage on the other hand was only 393 $\mu\varepsilon$ at 90 days. Persson (2001) compared the shrinkage and creep of self compacted and normal concrete and did not find any significant difference. Assié et al. (2006) evaluated the durability and transport properties of self compacting concrete. The chloride diffusion and water absorption revealed the transport properties of both concretes were found to be of the same order.

This paper presents the results of a combined experimental-numerical approach with non-linear finite element analysis used to compute moisture diffusivity and surface transfer coefficient for two types of self compacting concrete and compared with normal concrete incorporating silica fume. The effect of simultaneously high temperature and wind on diffusivity and shrinkage of self compacting concrete is also evaluated.

2 MOISTURE TRANSPORT AND DIFFUSIVITY OF CONCRETE

The moisture transport in concrete is driven by the moisture potential generated by a lower ambient humidity to which the saturated concrete is exposed. It involves a complex interaction between different transport processes. A phenomenological approach in which various transport mechanisms are lumped together by defining "diffusivity" of the material at a macroscopic level provides a convenient way to address the problem. Diffusivity is defined as the rate of vapor and liquid transport in the domain of the system without distinction of different moisture flow mechanisms, which are considered in an integral form (Baluch et al. 2002). The diffusivity of concrete is influenced by several material related and environmental factors including the moisture content, W/C ratio, presence of cracks, addition of silica fume or other admixtures, period of initial curing, and aggregate/cement ratio of the concrete. The moisture transport is also significantly affected by external influences such as ambient temperature and wind velocity.

Jooss & Reinhardt (2002) have discussed the influence of temperature on permeability and moisture diffusivity of concrete. Cerny et al. (2001) have studied the moisture diffusivity of two high performance concrete and found that the moisture diffusivity increases by about 100-200% at higher temperatures. Rahman (1999) also found that the diffusivity of cementitious mortars is significantly affected by ambient temperature. Studies carried out on flowing microconcrete (similar to SCC) used as repair mortar shows that the diffusivity increases three folds when the temperature is increased from 30°C to 50°C.

The governing differential equation (Fick's law) for moisture diffusion in concrete is given as:

$$\frac{\partial C(x_k,t)}{\partial t} = \frac{\partial}{\partial x_i}\left[D(C)\,\frac{\partial C(x_k,t)}{\partial x_i}\right] \quad \begin{array}{l} k = 1,2,3 \\ i = 1,2,3 \end{array} \tag{3}$$

Initial Conditions: $C(x_k,0) = C_o$ @ t=0 k=1,3 (4)

Convection Boundary Condition

$$D(C)\frac{\partial C(x_i,t)}{\partial x_i} n_i - h_f\,(C_e - C_s) = 0 \quad x_i \in \Gamma q \tag{5}$$

$C = C(x_i, t)$, i=1, 3 is the moisture content varying in domain with time, $D(C)$=Isotropic moisture diffusivity coefficient which is function of C, n_i is the outward normal at the boundary, h_f is the convective moisture transfer coefficient, C_e is the moisture of external environment, C_s is the surface moisture content of the solid, and $\partial C / \partial \underset{\sim}{n}$ is the moisture flux normal to the exposed surface.

The matrix differential equation governing moisture diffusion in a finite element system containing 'n' nodes, derived from Equation 3 and 5 is given as

$$\underline{M}(C)\,\dot{\underset{\sim}{C}}(t) + \underline{V}\,\underset{\sim}{C}(t) = \underset{\sim}{F} \tag{6}$$

where $\underline{M}(C)$ = Moisture diffusivity matrix, $\underline{V}$ = Moisture velocity matrix, $\underset{\sim}{C}(t)$ =Vector of nodal moisture at time t, $\dot{\underset{\sim}{C}}(t)$ =Vector of time rate of change of nodal moisture, and $\underset{\sim}{F}$ = Vector of external moisture load.

Equation 6 represents a set of nonlinear equations, which is to be solved over the finite element domain to obtain the nodal moisture content as a function of time. The transient nature of this equation is accounted for by a step-by-step time integration scheme. The moisture content at time t = 0, $\underset{\sim}{C}(0)$ is known apriori. In this scheme, the time is incremented by Δt and the equation is solved to obtain the moisture content C_1 at time t_1. The process is repeated, gradually generating a sequence of moisture states in the domain $\{\underset{\sim}{C}_o, \underset{\sim}{C}_1, \underset{\sim}{C}_2, \ldots\ldots\ldots \underset{\sim}{C}_n\}$, approximating the moisture content history $\underset{\sim}{C}(t)$ in the domain.

3 EXPERIMENTAL PROGRAM

The experimental program involved principally drying tests to determine the moisture diffusivity of three types of concrete under varying exposure conditions. Slump, compressive and tensile strength, and shrinkage tests, were also conducted. The types of concrete used include:

- Self compacting concrete (SCC) with ultra fine fly ash, high range water reducing admixture and dispersing agent based on polycarboxylate polymer technology,
- Enhanced self consolidating concrete (ESCC), in which normal concrete is used with the addition of polycarboxylic ether polymer that it is based on a unique nanotechnology with long lateral chains, and
- Silica fume concrete (SFC) which is used extensively in this region, with sulphonated naphthalene polymer based superplasticizer was taken as the reference concrete.

The mixture proportion for the three types of concrete used is shown in Table-1. The average 28-days compressive strength for SCC, ESCC and SFC is 47.5 MPa, 46.6 MPa, and 47.1 MPa respectively.

Table 1. Mixture Proportion of the Concreter (/m^3).

Ingredients	SCC	ESCC	SFC
Water, kg	180.5	180	154
Portland cement, kg	425	500	355
Ultrafine fly ash, kg	106	0	0
Silica fume, kg	0	0	30
Fine aggregate, kg	800	924	680
Coarse aggregate, kg	840	762	1110
High-range water-reducing admixture, kg	4.25	0	0
Dispersing agent, kg	7.0	0	0
Viscosity-modifying agent, lit/100kg	0	1.6	0
Superplasticizer, lit/100kg	0	0	1.4
Water/binder ratio	0.34	0.36	0.4
Slump or slump flow diameter of spread, mm	750	710	106

3.1 *Drying tests*

Drying tests were conducted on specimens with varying length of path of unidirectional moisture movement. These tests were carried out for computing diffusivity of concrete under various environmental conditions including wind and temperature to study their effect on diffusivity and/or surface transfer coefficient. Specimens of four different widths (25, 50, 75, & 100 mm) but similar cross sectional area (100x100 mm) were used for 1-D drying test for computing moisture diffusivity. These tests were carried out on the three types concrete mixes for a period of 6-8 weeks, inside the environmental chambers shown in Figure 1, with controlled wind, humidity and temperature.

The tests were performed at two different conditions, representing a normal and an extreme environment. In normal environment the temperature was kept at 30±2 °C with a low wind speed of 6 km/hr. The extreme environment was represented by a high temperature of 50±2 °C and a wind speed of and 22 km/hr. The environmental humidity being a key factor in extorting moisture from the concrete specimens was kept constant and low at 40% R.H in all experiments to enhance the moisture transport in the specimen.

After casting of concrete, all specimens were cured in moulds and sealed in plastic wraps for 24 hours. They were then demoulded and cured under wet burlap for 7 days. The specimens were then sealed with high temperature silicon and one layer of aluminum tape along the thickness to ensure moisture movement/diffusion in one dimension only. Initial weight of each specimen was recorded and it was transferred to the environmental chamber for drying. The specimens were weighed at regular intervals with frequent intervals during the first three days tapering to one reading each week to generate enough data points for setting up the moisture loss curves. Afterwards they were dried in an oven at 105+5°C to determine the evaporable moisture content to compute the percentage of moisture loss in the specimen.

Figure 1. Pyrex glass (low wind) and steel (high wind) environmental chambers with drying specimens.

4 EXPERIMENTAL RESULTS

4.1 *Moisture loss for the three types of concrete*

Figures 2 and 3 shows the moisture lost percentage in 25 mm and 75 mm thick specimens at an ambient temperature of 30°C and wind speed of 6 km/hr. Moisture loss in 25 mm thick specimens of SCC, SFC and ESCC, at an age of 28 days, is about 31%, 33%, and 34% respectively. It can be seen that during the first 1-2 days moisture loss is almost similar for all the concretes but diverges later with no significant moisture loss after 35 days for SFC and ESCC at age of 55 days for SCC. For 75 mm thick specimens the moisture loss in SCC, SFC, and ESCC is about 28%, 27% and 32% respectively. It is evident from these figures that SCC and SFC have almost same moisture loss at all ages, whereas, ESCC has slightly higher moisture loss. At an ambient temperature of 50°C and wind speed of 22 km/hr, Figures 4 and 5 shows that moisture loss increased for all types of concrete. In thin 25 mm thick specimens after about 20-25 days of exposure the moisture loss curves in all concrete flatten out indicating a rapid loss of moisture as compared to the normal exposure. The moisture loss in 75 mm thick specimens in SCC, SFC, and ESCC is about 35%, 37% and 43% of the evaporable moisture at 28 days.

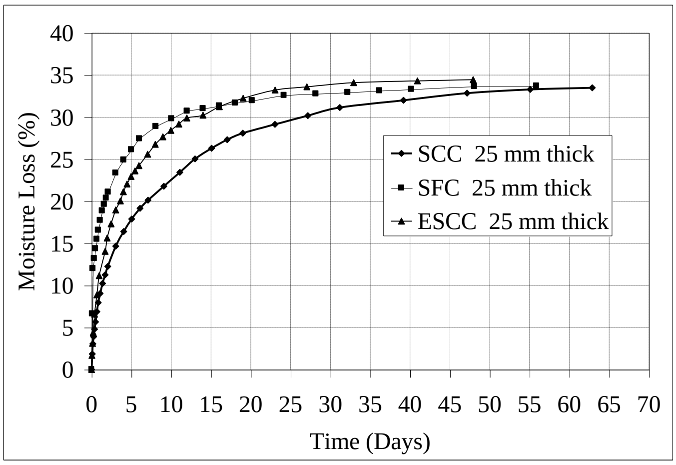

Figure 2. Moisture loss (%) in 25-mm thick specimen at 30°C and 6 km/hr wind.

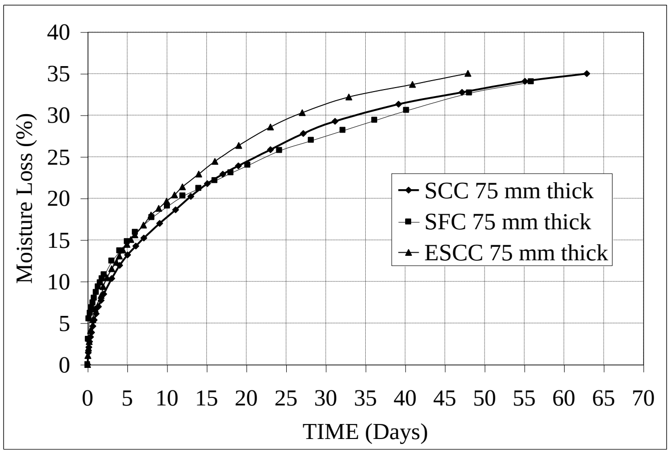

Figure 3. Moisture loss (%) in 75-mm thick specimen at 30°C and 6 km/hr wind.

4.2 *Effect of high temperature and wind on moisture loss*

The effect of high temperature on moisture loss for the three types of concrete is shown in Figures 6 - 8. High temperature coupled with high wind representing extreme environment significantly affects the percentage of moisture lost in all concrete mixes. The moisture loss at 50^0C with a high wind of 22 km/hr is about 12-14% higher in SCC and SFC and 10-12% in ESCC as compared to moisture loss at 30°C and low wind of 6km/hr at 28 days.

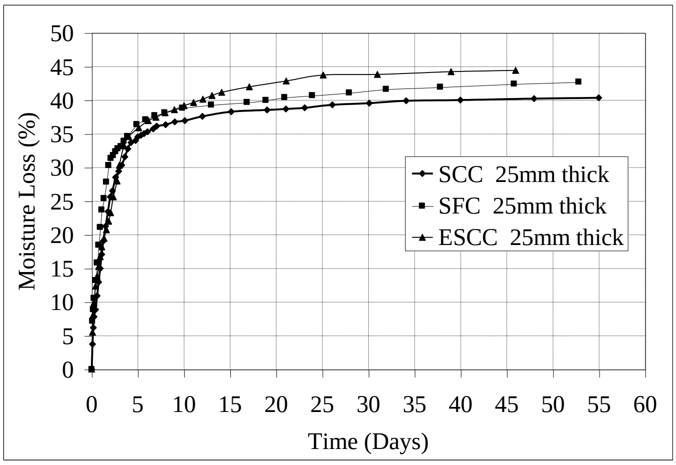

Figure 4. Moisture loss (%) in 25-mm thick specimen at 50°C and 22 km/hr wind.

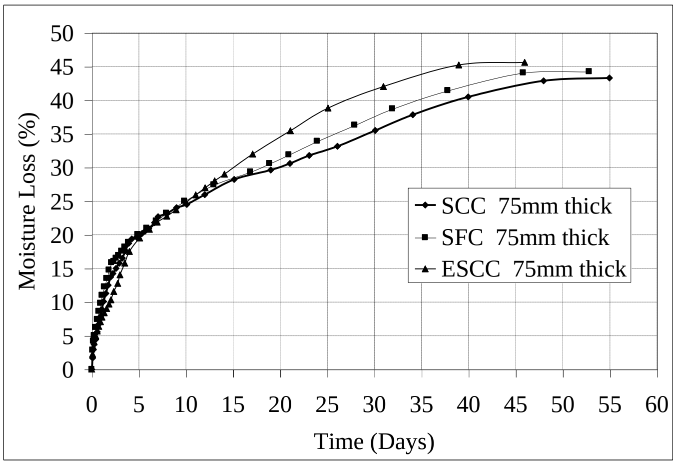

Figure 5. Moisture loss (%) in 75-mm thick specimen at 50°C and 22 km/hr wind.

In SCC at low wind speed and low temperature 75 mm thick specimen lost 32% of the total evaporable moisture, while under high wind and high temperature the moisture loss was 44%, after 40 days of exposure.

The initial slope of the moisture loss curve can be observed to be steeper at high wind speed and high temperature. The moisture loss gets accelerated with the increase in wind speed because of higher convective moisture transfer at the surface. Also at higher temperature there is increase in energy of water vapor molecules and expansion of pores which enhances the moisture diffusion in domain.

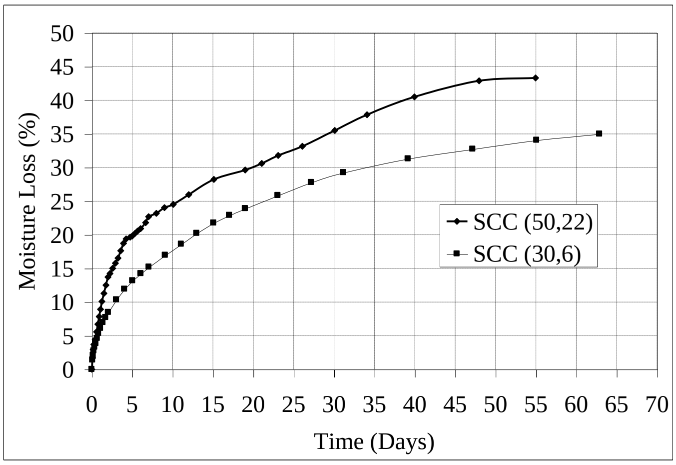

Figure 6. Effect of environment on moisture loss (%) for SCC (75-mm thick specimen).

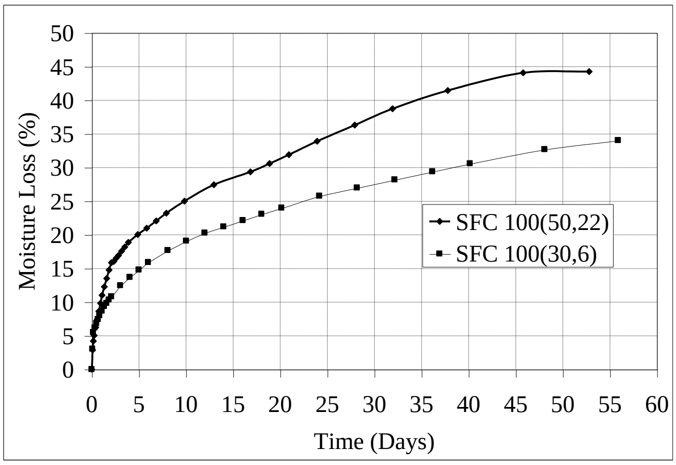

Figure 7. Effect of environment on moisture loss (%) for SFC (75-mm thick specimen).

5 COMPUTATION OF MOISTURE DIFFUSIVITY OF CONCRETE

The computational models for diffusion of moisture in concrete require an empirical moisture diffusivity law for computations of time history of moisture content over the spatial domain of the element. Determination of moisture diffusivity of concrete is contingent upon precise measurement of moisture loss as a function of space and time. At present no simple experimental technique is available for such precise measurements. Sophisticated methods such as nuclear magnetic resonance and computer tomography have been developed recently but these methods are not readily available.

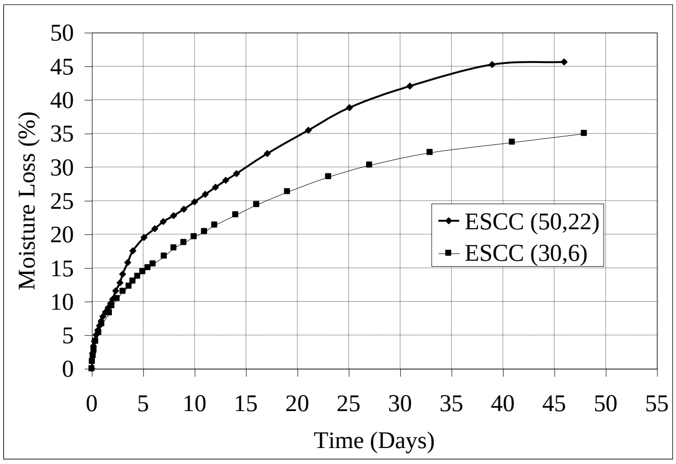

Figure 8. Effect of environment on moisture loss (%) for ESCC (75-mm thick specimen).

Several methods have been reported in literature for determination of diffusivity of cementitious mortar and concrete. The Boltzmann-Matano method has been used in several studies. A combined experimental-finite element based approach is used in this study for computing moisture diffusivity. A 2-D non-linear finite element method combined with nonlinear least squares fit method is used for the formulation of the diffusivity law for concrete. The non-linear finite element program DIANA-2D (DIffusion ANAlysis) (Module of program DISH-2D) developed by Rahman (Rahman 1999) is used in this study for this purpose.

Different investigators have used different forms of dependence of diffusivity D on the moisture content. In concrete specimen subjected to high temperature and wind speeds, it was observed that the moisture loss-time curve is steep at early ages. This corresponds to a rapid loss of moisture initially, which decreases substantially at a later age. A diffusivity law with a trigonometric tangent function proposed by Rahman (Rahman 1999) with three unknown parameters is incorporated in DIANA-2D for computing the diffusivity of self compacting concrete.

$$D(C) = b_o \tan (b_1 C^n) \tag{6}$$

where b_o, b_1 and n are parameters to be evaluated for best fit.

Numerical evaluation of diffusivity law parameters and convective transfer coefficient (h_f), for each type of concrete mix under each exposure regime is carried out using an iterative technique. This iterative technique involves numerical computation of moisture loss over the domain of the experimental sample with appropriate boundary conditions followed by computation of the mean moisture loss in the sample using an assumed set of values b_0, b_1 & n. Iterative runs were first carried out for the 100x100x75 mm specimen to ascertain the values of b_0, b_1, n & h_f., which best fits the experimental moisture loss (%) data. Later the computed parameter values were verified for specimens of other thickness with some fine-tuning the parameters. Experimental and computed moisture loss curves for SCC, ESCC, and SFC is shown in Figures 9-11 for selected cases. Good correlation between the experimental and computed moisture loss data for the selected parameter values is evident. The regression parameters of the diffusivity law which gives the best fit for 6 sets of experiments conducted are shown in Table 2.

Table 2. Parameters for diffusivity law.

Concrete	Temp Wind °C km/hr		h_f cm/d	b_0	b_1	n	D_{av} cm^2/d
SCC	50	22	4.0	2.5	0.5	5.48	0.204
SFC	50	22	4.0	2.5	0.5	5.55	0.202
ESCC	50	22	4.0	2.5	0.5	4.98	0.221
SCC	30	6	0.2	2.0	0.8	9.0	0.183
SFC	30	6	0.5	2.0	0.8	9.1	0.182
ESCC	30	6	0.25	2.0	0.8	8.23	0.198

It can be observed that under high temperature and high wind the convective moisture transfer at the surface of concrete increases several folds for the two self compacting concretes. The increase transfer coefficient (h_f) under extreme environment is 20 times as compared to the normal environment for self compacting concretes and 8 times for the silica fume concrete. Under normal environment the convective moisture transfer coefficient in self compacting concretes is half of the concrete with silica fume.

A mean diffusivity (D_{av}) for the self compacting concrete can be computed as the area under the diffusivity-moisture content curve normalized by the moisture content interval. A typical curve under two selected environmental conditions is shown in Figure 12.

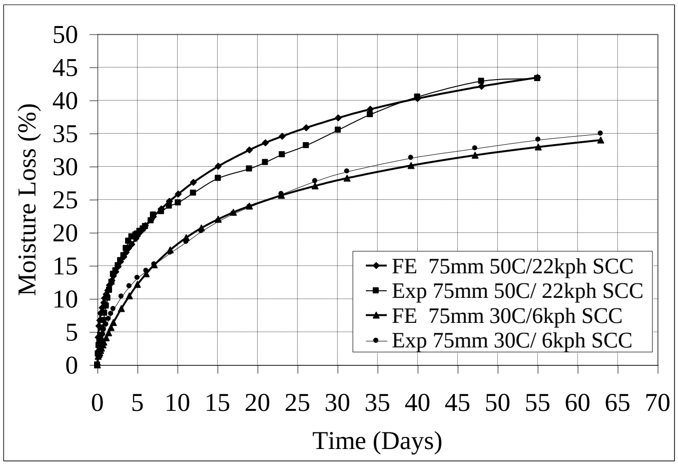

Figure 9. Finite element & experimental mean moisture loss (%) for SCC (75-mm thick)

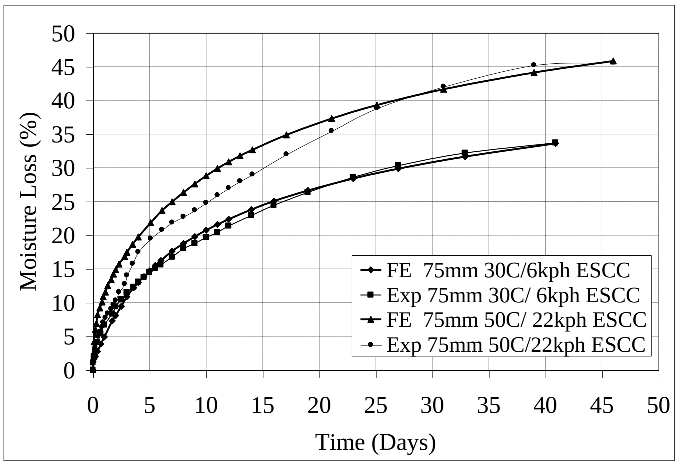

Figure 10. Finite element & experimental mean moisture loss (%) for ESCC (75-mm thick)

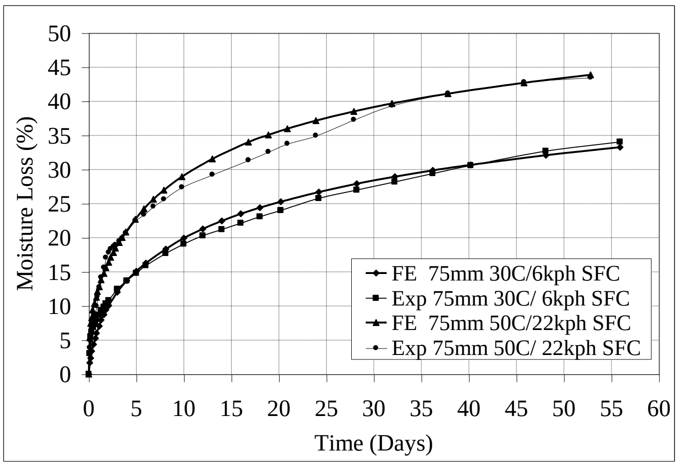

Figure 11. Finite element & experimental mean moisture loss (%) for SFC (75-mm thick)

From Table 2 it can be seen that the average diffusivity of ESCC is about 6-8% higher as compared to SCC and SFC. The average diffusivity of SCC, SFC and ESCC increases by 11-12% as the environment changes from low temperature-low wind to high temperature-high wind. It can be concluded that under extreme environmental conditions, the moisture loss from self compacting concrete will be significantly higher leading to higher drying shrinkage.

The measured shrinkage strain at 28 days for SCC, ESCC, and SFC is shown in Table 3. It can be seen that the total shrinkage strain at 28 days is in SCC is about 32% higher for both environments as compared to SFC, whereas it is about 74% and 83% higher in ESCC as compared to SFC under the two environmental conditions. The shrinkage strain in ESCC is about 30% and 40% higher as compared to SCC for the two exposure condition. The effect of extreme environment on all concretes is an increase in shrinkage strain in the range of 18-25%. The increase in moisture diffusion and associated shrinkage in self compacting concretes can be attributed to the significantly higher fines present in self compacting concrete. It is anticipated that autogenous shrinkage in self compacting concrete could be significantly high and this needs further investigations.

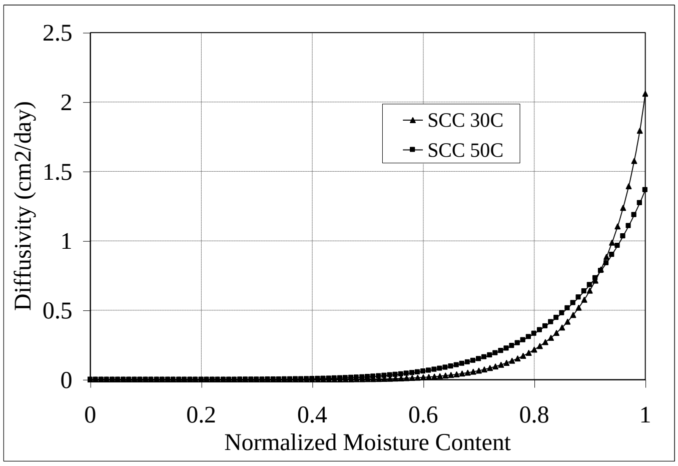

Figure 12. Effect of temperature on diffusivity SFC

Table 3. Measured Shrinkage Strain at 28 days

Concrete	Shrinkage strain at 28 days (με)	
	30°C – 6 km/hr	50°C – 22 km/hr
SFC	290	360
SCC	380	480
ESCC	530	625

6 CONCLUSIONS

A combined experimental-finite element approach is used to study the moisture diffusivity of self compacting and silica fume concrete under normal and extreme conditions. A diffusivity law in tangent trigonometric form gives a good correlation between observed and computed moisture loss in self compacting concrete. Nonlinear finite element can used to accurately predict moisture loss in concrete members in spatial and time domain. The moisture transport is found to be significantly affected by high temperature and wind. The convective moisture transport coefficient increases several fold with higher moisture loss under high temperature and high wind condition. The average diffusivity of ESCC is significantly higher as compared to SCC and SFC.

The shrinkage strain in SCC is found to increase significantly (30% higher) as compared to the silica fume concrete. The ESCC on the other hand shows a very high shrinkage strain (75-85% higher) as compared to silica fume concrete. This increase is observed under both normal and extreme environmental conditions. The shrinkage strain also increases (18-25%) under extreme environmental conditions. This will result in higher stresses in the restrained self compacting concrete members and will cause cracking if tensile strength of concrete is exceeded. From moisture diffusivity and measured shrinkage in self compacting concrete, it can be inferred that the autogenous shrinkage in self compacting concrete could be significantly higher as compared to the silica fume concrete.

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