

Analysis of self-desiccation of high performance concrete considering effects of mixing proportions and curing conditions

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Abstract

High performance concrete is increasingly used in modern concrete industry to produce buildings and infrastructures. However, because high performance concrete generally has lower water to binder ratios than normal strength concrete, high performance concrete presents higher self-desiccation, higher autogenous shrinkage, and higher early-age crack tendency than normal strength concrete. This paper presents a numerical procedure to analyze self-desiccation of high performance concrete. By using a blended cement hydration model, the reaction degree of cement and mineral admixtures are calculated. The amount of chemical shrinkage, capillary water, and gel water are calculated using reaction degree of binders. Using a desorption isotherm consisting of capillary isotherm and gel isotherm, the self-desiccation of concrete are calculated. The effects of water to binder ratios, silica fume replacement ratios, fineness of cement, curing temperature, and curing conditions (sealed curing and wet curing) are taken into account. The analyzed results agree with experiment results of concrete with different mixing proportions and curing methods.

Keywords: High performance concrete; Self-desiccation; Curing temperature; Curing methods; Silica fume

INTRODUCTION

High performance concrete is widely used in modern concrete industry to produce buildings and infrastructures. High performance concrete has many advantages, such as reduction in size of the columns, high workability and pump ability, improved durability in aggressive environment, and low maintenance cost. However, high performance concrete also has disadvantages, such as high self desiccation, high autogenous shrinkage, and high early-age crack tendency. Self desiccation is the reduction of relative humidity due to

consumption of capillary water in the progress of cement hydration. Autogenous shrinkage is the macroscopic volume reduction of cement based materials when cement hydrates after initial setting. Self desiccation is one of main reasons of autogenous shrinkage and early-age crack of concrete [1].

Experimental study and theoretical analysis about self-desiccation are abundant. Kim and Lee [2] measured relative humidity in hardening concrete with different water to cement ratios and wet curing periods. They found that concrete with lower water to binder ratios and shorter wet curing periods presents higher self-desiccations. Jensen and Hansen [3] found that with the increasing of curing temperatures, the rate of self-desiccation increases. Silica fume blended concrete shows higher self desiccation than control concrete[1,3]. Bentz et al.[4] found that concrete containing coarser cements show lower degree of hydration and self-desiccation than concrete containing finer cement. Besides wet curing, internal curing methods using superabsorbent polymers [5] and light weight aggregate [6] is effective to reduce self-desiccation and autogenous shrinkage of high strength concrete.

Compared with abundant experimental study [1-6], theoretical study about self desiccation is relatively limit. Radocea [7] proposed a self desiccation model as a function of degree of hydration, cement content, and initial water content. But Radocea's model [7] does not consider the difference between capillary isotherm and gel isotherm. Nilsson and Mjonell [8] proposed a model considering the capillary isotherm and gel isotherm, and evaluated moisture capacity of concrete with different degree of hydrations. Using Nilsson and Mjonell's desorption model [8], Oh and Cha [9] evaluated self-desiccation of hardening Portland cement concrete with different water to cement ratios and curing temperatures. Using a microstructural cement hydration model considering cement

particle size distributions, cement mineral compositions, water to cement ratios, and curing temperatures [10], Koenders and Breugel [11] simulated thermodynamic equilibrium in the capillary pore space, change of surface tension force, and self-desiccation in hardening cement paste. It should be noticed that the proposed models in references [7-11] are only for Portland cement concrete. For blended cement, due to the coexistence of cement hydration and mineral admixtures reactions, the models in references [7-11] are not valid. Luzio and Cusatis [12-13] proposed a hydration model for silica fume blended concrete and evaluated self-desiccation of silica fume blended high performance concrete. However, the effect of wet curing on self-desiccation is not considered in Luzio and Cusatis' [12-13] study.

To overcome the weak points in references [7-13] and systematically evaluate the self desiccation of high performance concrete, this paper presents a self desiccation model for concrete incorporating mineral admixtures. By using a blended cement hydration model considering mixing proportions and curing methods, the reaction degree of cement and mineral admixtures, chemical shrinkage, capillary water, and gel water are calculated. Using a desorption isotherm consisting of capillary isotherm and gel isotherm, the self-desiccation of hardening concrete are calculated.

CEMENT HYDRATION MODEL AND SELF DESICCATION MODEL

Cement Hydration Model

Wang and Lee [14-18] proposed a hydration model for concrete containing supplementary cementitious materials, such as silica fume, fly ash, slag, and rice husk ash. Hydration equations for cement and mineral admixtures are respectively proposed, and the mutual interactions between cement hydration and mineral admixtures reaction are considered through capillary water contents and calcium hydroxide contents. The hydration model is valid for concrete with different water to binder ratios, mineral admixture replacement ratios, and curing temperatures [14-18].

Hydration degree of cement and reaction degree of mineral admixtures are used as fundamental indicators to evaluate properties development of concrete. Degree of cement

hydration (α) is defined as the ratio of mass of hydrated cement to mass of cement in the mixing proportion. The value of degree of cement hydration (α) ranges between 0 and 1. Degree of cement hydration $\alpha=0$ means hydration does not start, and degree of cement hydration $\alpha=1$ means cement has fully hydrated.

By using an integration method, degree of cement hydration can be determined as follows:

$$\alpha = \int_0^t \left(\frac{d\alpha}{dt} \right) dt \quad (1)$$

where t is time, $\frac{d\alpha}{dt}$ is rate of cement hydration. The detailed equations for $\frac{d\alpha}{dt}$ are available in our former research [14-18]).

Similarly, reaction degree of mineral admixtures (α_M) is defined as the ratio of mass of reacted mineral admixture to mass of mineral admixture in the mixing proportion. The value of reaction degree of mineral admixture (α_M) ranges between 0 and 1. $\alpha_M=0$ means mineral admixture reaction does not start and $\alpha_M=1$ means all the mineral admixture has reacted.

Reaction degree of mineral admixture also can be determined using an integration method in time domain as follows:

$$\alpha_M = \int_0^t \left(\frac{d\alpha_M}{dt} \right) dt \quad (2)$$

where $\frac{d\alpha_M}{dt}$ is rate of mineral admixture reaction. The detailed equations for $\frac{d\alpha_M}{dt}$ are available in our former research [14-18]).

Chemically bound water relates to both cement hydration and mineral admixture reaction. The chemically bound water contents can be determined as follows:

$$W_{cbm}(t) = 0.25 * C_0 * \alpha + v_M * M_0 * \alpha_M \quad (3)$$

where W_{cbm} is chemically bound water content, C_0 is the

mass of cement in the mixing proportion, v_M is chemically bound water from per unit mass reacted mineral admixture, and M_0 is mass of mineral admixture in the mixing proportions. $0.25 * C_0 * \alpha$ is the mass of chemically bound water from cement hydration, and $v_M * M_0 * \alpha_M$ is the mass of chemically bound water from mineral admixture reaction [14-18].

In cement-mineral admixture blends, capillary water is consumed from cement hydration and mineral admixture reaction. The capillary water contents can be calculated as follows:

$$W_{cap}(t) = W_0 - 0.4 * C_0 * \alpha - v_M * \alpha_M * M_0 - v_{PW} * \alpha_M * M_0 \quad (4)$$

where W_{cap} is the mass of capillary water in hardening concrete, W_0 is the mass of water in the mixing proportion, and v_{PW} is the mass of physically bound water from per unit mass reacted mineral admixture. $0.4 * C_0 * \alpha$ is the mass of consumed capillary water from cement hydration, and $v_M * \alpha_M * M_0 + v_{PW} * \alpha_M * M_0$ is the mass of consumed capillary water from mineral admixtures reaction [14-18]. Equation (4) is valid for sealed curing concrete. For wet curing concrete, due to imbibition of water from surrounding environment, the amount of capillary water is higher than that calculated from equation (4).

In cement-mineral admixture blends, cement hydration and mineral admixture reaction contribute the formation of gel water. The content of gel water contents can be calculated as follows:

$$W_{gel}(t) = 0.15 * C_0 * \alpha + v_{PW} * \alpha_M * M_0 \quad (5)$$

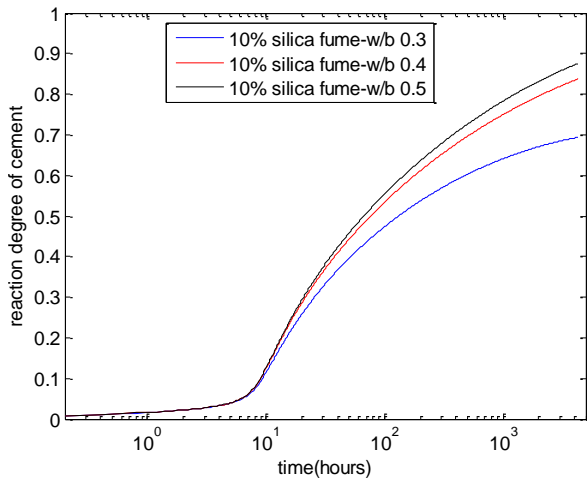
where W_{gel} is the mass of gel water. $0.15 * C_0 * \alpha$ is the mass of gel water produced from cement hydration, and $v_{PW} * \alpha_M * M_0$ is the mass of gel water produced from mineral admixture reaction.

Cement hydration produces calcium hydroxide, and mineral admixture reaction consumes calcium hydroxide. Considering the producing and consuming of calcium hydroxide, calcium hydroxide contents in cement-mineral admixture blends can be determined as follows:

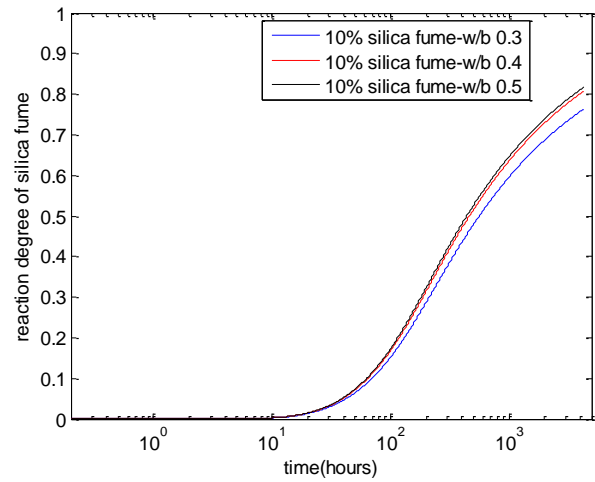
$$CH(t) = RCH_{CE} * C_0 * \alpha - v_{MCH} * \alpha_M * P \quad (6)$$

where CH is the mass of calcium hydroxide, RCH_{CE} is the mass of calcium hydroxide produced from per unit mass hydrated cement, and v_{MCH} is the mass of calcium hydroxide consumed from per unit mass reacted mineral admixture. $RCH_{CE} * C_0 * \alpha$ is the produced calcium hydroxide from cement hydration, and $v_{MCH} * \alpha_M * P$ is the mass of consumed calcium hydroxide from mineral admixture reaction.

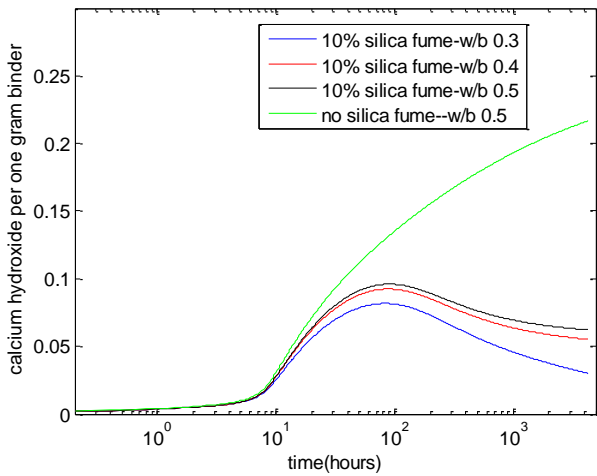
Parameter analysis of blended cement hydration model are shown in Figure 1. As shown in Figure 1-a and Figure 1-b, with the reduction of water to binder ratios, due to the limitations of available spaces for hydration products, reaction degree of cement and silica fume decrease. As shown in Figure 1-c, for control Portland cement concrete, calcium hydroxide content continuously increases due to cement hydration while for silica fume blended concrete, at early ages, calcium hydroxide content initially increases because cement hydration is more dominant than silica fume reaction. After reaching a peak, calcium hydroxide content decreases because the consumption of calcium hydroxide from silica fume reaction. As shown in Figure 1-d, when water to binder ratio is same, with the increasing of silica fume replacement ratios, calcium hydroxide contents decrease.



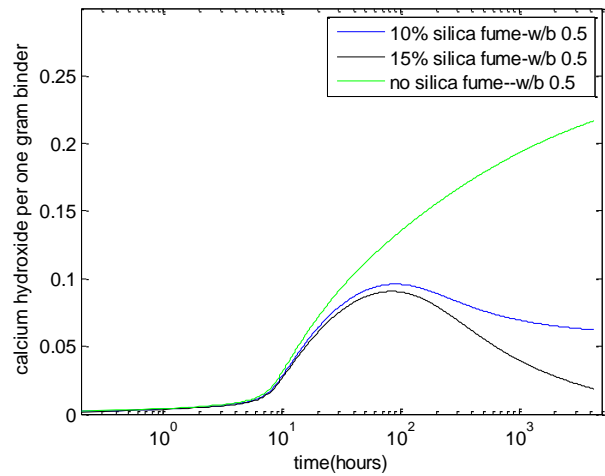
(1-a) reaction degree of cement



(1-b) reaction degree of silica fume



(1-c) calcium hydroxide contents with different water to binder ratios



(1-d) calcium hydroxide contents with different silica fume replacement ratios

Figure 1. Parameter analysis of hydration model

Self desiccation model

Nilsson and Mjonell [8] proposed a model for evaluating on self-desiccation in hardening high performance concrete. In this model, the effect of degree of hydration on desorption isotherm is considered. The desorption isotherm of hardening concrete is decomposed into two parts: gel desorption isotherm and capillary desorption isotherm. The relations among total desorption isotherm, capillary desorption isotherm, and gel desorption isotherm are shown as follows:

$$\frac{W_e(h, \alpha)}{C_0} = \gamma_{gel} \frac{W_{gel}(h, \alpha)}{C_0} + \gamma_{cap} \frac{W_{cap}(h, \alpha)}{C_0} \tag{7}$$

$$\gamma_{gel} = 1 - \frac{1}{\exp(b - 10\alpha)h} \tag{8}$$

$$\gamma_{cap} = \exp(b - 10\alpha)h - 1 \tag{9}$$

where W_e is the mass of evaporable water; γ_{gel} is filling factor of gel water; γ_{cap} is filling factor of capillary water; b denotes shape factor of desorption isotherm (the value of shape factor ranges from 8 to 12[8]).

The self-desiccation $\frac{\partial h_s}{\partial t}$ due to cement hydration can be determined as follows [8-9]:

$$h_s = \frac{1}{b-10\alpha} \left(\sqrt{W_e^2 + 2W_e(W_{cap} - W_{gel}) + W_{gel}^2 + 2W_{cap}W_{gel} + W_{cap}^2 + W_e - W_{gel} + W_{cap}} \right) / 2W_{cap} \quad (10)$$

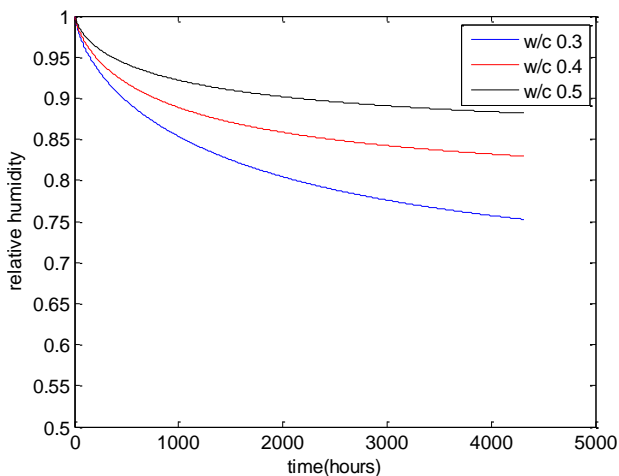
The proposed numerical procedure has considered the effects of water to binder ratios, mineral admixture replacement ratios, curing temperatures, fineness of binders, mineral compositions of binders, and curing methods on self-desiccation. The self-desiccation model is combined with cement hydration model. By using hydration model (equation (4) and equation (5)), W_{cap} and W_{gel} can be calculated. Then by using equation (7), W_e can be calculated. Finally, using self-desiccation

model (equation (10)), the relative humidity reduction due to self desiccation can be calculated.

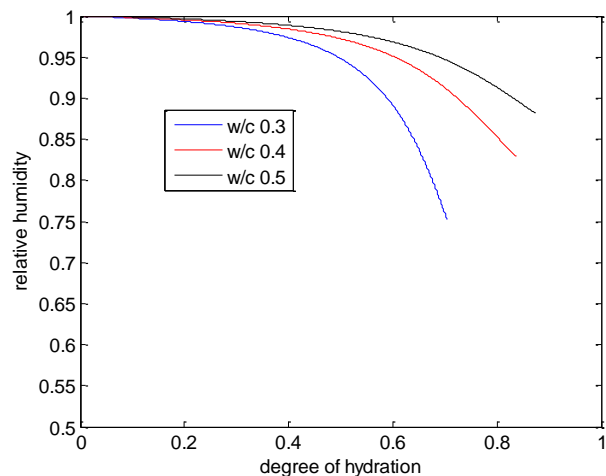
VERIFICATION OF PROPOSED MODEL

Effect of water to cement ratios on self-desiccation

Self-desiccation is significantly influenced by water to cement ratios of concrete. As shown in Figure 2-a, with the decreasing of water to cement ratios, relative humidity reduction due to self-desiccation becomes more obvious. At early ages, relative humidity decreases at a higher rate. And at late ages, the rate of self desiccation is marginal. As shown in Figure 2-b, at late ages, for concrete with lower water to cement ratio, a small increase of degree of hydration can lower relative humidity significantly.



(2-a) RH as function of curing ages



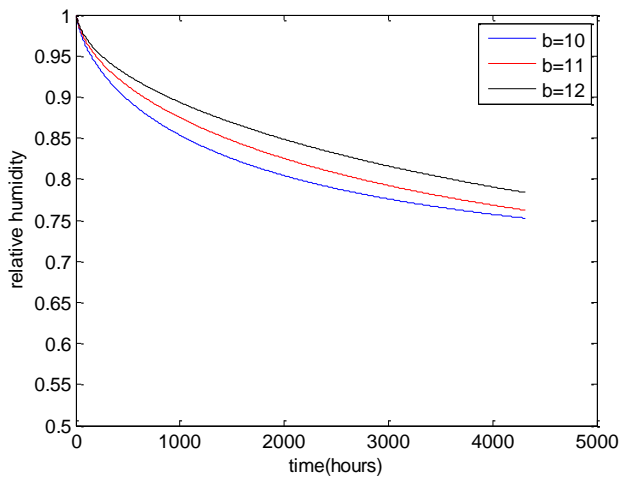
(2-b) RH as function of degree of hydration

Figure 2. Effect of water to cement ratios on self-desiccation

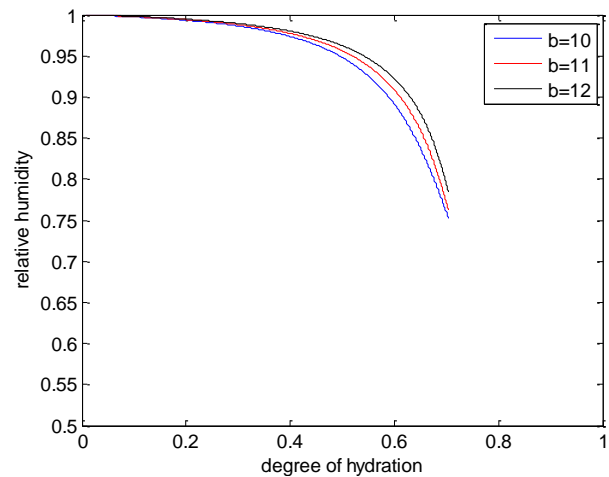
Effect of shape factor on self-desiccation

In equation (8) and equation (9), shape factor b is an empirical parameter which can be calibrated from desorption isotherm of concrete with constant degree of hydration. Oh and Cha [9] proposed that shape factor is dependent on type of cement, water to cement ratios, and silica fume additions. As shown in

Figure 3-a and 3-b, when other parameters are same, with the decreasing of shape factor, relative humidity shows more reductions. Hence for concrete with much finer capillary pores, a lower shape factor should be used.



(3-a) RH as function of curing ages



(3-b) RH as function of degree of hydration

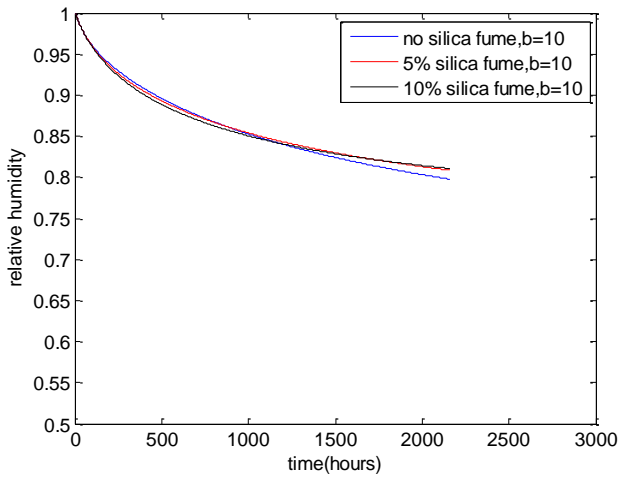
Figure 3. Effect of shape factor on self-desiccation ($w/c=0.3$)

Effect of silica fume replacement ratios on self-desiccation

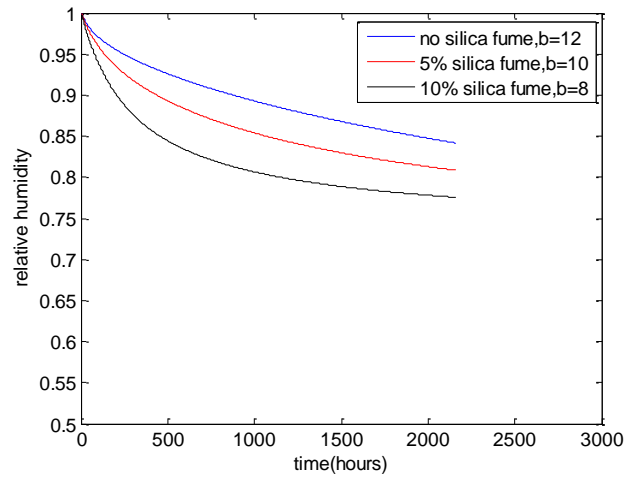
Silica fume is widely used in producing high performance concrete. The addition of silica fume in concrete shows many advantages. First, silica fume has a smaller particle size than cement and can fill voids between cement grains. Second, silica fume enhances the rheological characteristics and silica fume forms hydration products by pozzolanic activity. Third, silica fume can improve the interfacial transition zones between binder and steel fibers. Thus, the mechanical strengths are increased and microstructure and packing efficiency of concrete are enhanced. However, silica fume also presents negative effect on concrete. The addition of silica fume increases the self desiccation, autogenous shrinkage, and early age crack of concrete.

Using the hydration model based self-desiccation model, the effects of silica fume additions on self desiccation can be

clarified. The water to binder ratio is 0.3, and silica fume replacement ratios are 0, 0.05, and 0.1 respectively. As shown in Figure 4-a, when shape factor is same ($b=10$) for different silica fume additions, relative humidity reductions are almost same. The tendency of analyzed results in Figure 4-a does not agree with experimental results (Jensen and Hansen [1] found that silica fume blended concrete shows higher self-desiccation than control concrete). On the other hand, as shown in Figure 4-b, when shape factors decrease as silica fume contents increase, concrete with higher silica fume additions show higher self-desiccation. The tendency of analyzed results in Figure 4-b agree with experimental results of Jensen and Hansen [1]. Summarily, for silica fume blended concrete, because of pore-size refinement and grain-size refinement effects from silica fume reactions [14], a lower shape factor b should be used.



(4-a) shape factor $b=10$



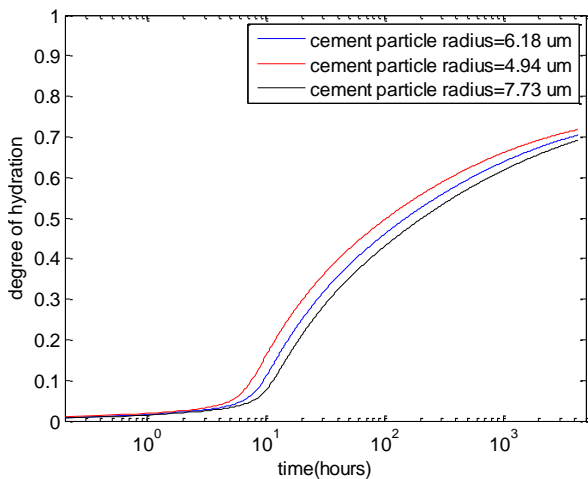
(4-b) shape factors decrease as silica fume contents increase

Figure 4. Effect of silica fume additions on self-desiccation ($w/b=0.3$)

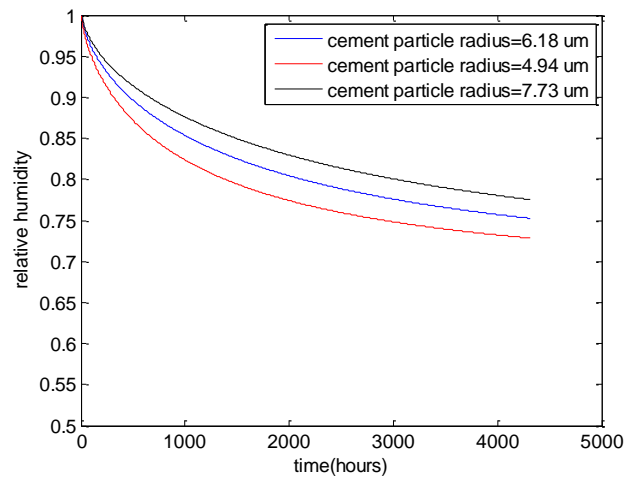
Effect of fineness of cement on self-desiccation

To increase reactivity and improve early-age strength of concrete, cement with a high Blaine surface is widely used. Figure 5 effect of fineness of cement on self desiccation. With the decreasing of cement particle size, cement reactivity increases, degree of hydration increase (Figure 5-a), and self desiccation increase (Figure 5-b). As shown in Figure 5-c,

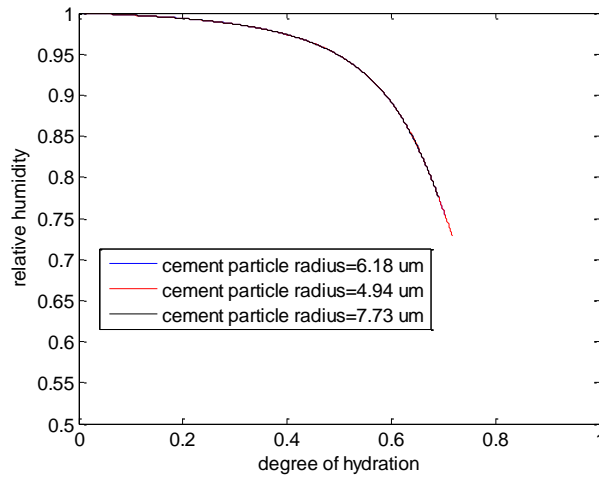
for cement with different fineness, the curves of self desiccation merge together. It means that hydration and chemical shrinkage induced empty air space is the fundamental reason for self desiccation. Bentz et al.[4] also found using coarser cement can reduce self desiccation of concrete, which is similar with analyzed results from our numerical model.



(5-a) degree of hydration



(5-b) RH as function of curing ages



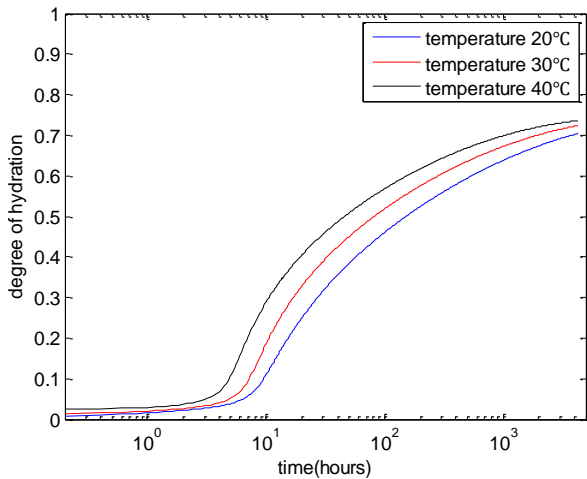
(5-c) RH as function of degree of hydration

Figure 5. Effect of fineness of cement on self-desiccation (w/b=0.3)

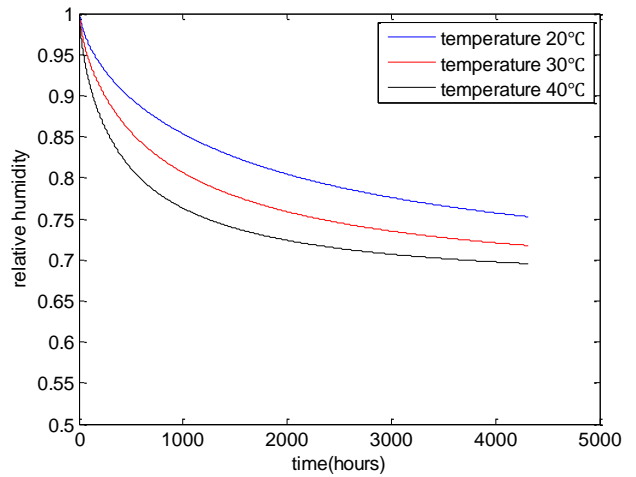
Effect of curing temperatures on self-desiccation

High temperature curing is widely used in concrete industry to accelerate hydration of cement, increase early age strength, and remove formwork early. Figure 6 shows effect of curing temperature on self desiccation. With the increasing of curing temperatures, degree of hydration increase (Figure 6-a), and

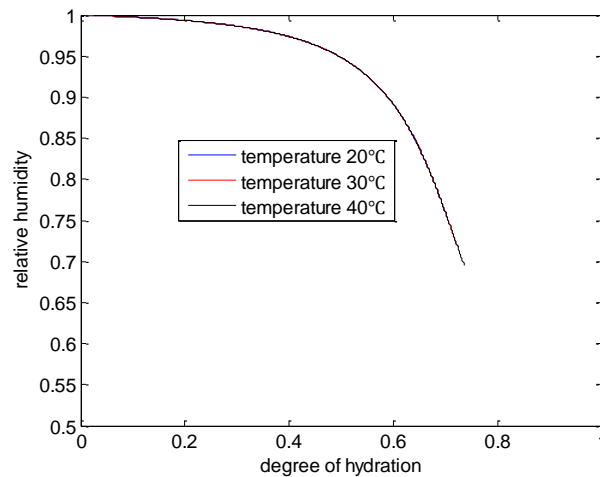
self desiccation increase (Figure 6-b). As shown in Figure 6-c, when self-desiccation is plot as function of degree of hydration, for cement with different curing temperatures, the curves of self desiccation merge together, which is similar with that shown in Figure 5-c.



(6-a) degree of hydration



(6-b) RH as function of curing ages



(6-c) RH as function of degree of hydration

Figure 6. Effect of curing temperature of cement on self-desiccation (w/b=0.3)

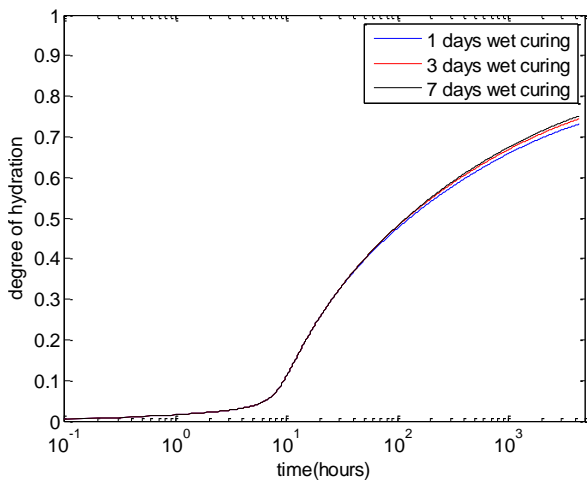
Effect of moist curing periods on self-desiccation

The analyzed results shown in sections 3.1 to 3.6 are for sealed curing concrete and no extra water is available. In construction sites, wet curing are widely used to improve the early-age hydration degree and compressive strength of concrete. For wet curing condition, the empty air space produced from chemical shrinkage can be fully or partially filled with imbibed water from surrounding wet environment [19-26]. The amount of capillary water for wet curing condition can be calculated as follows:

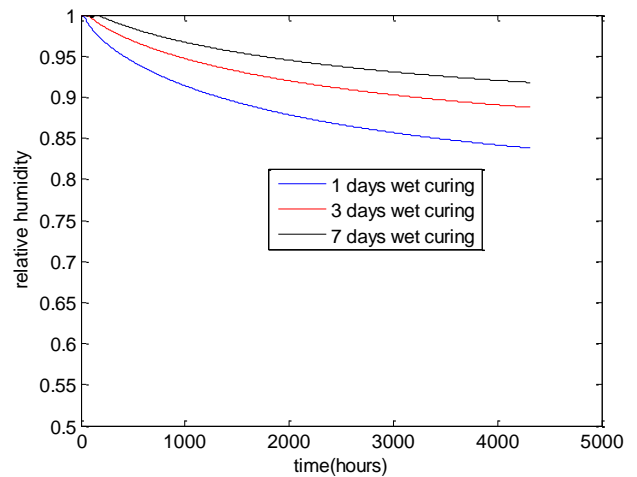
$$W_{cap}(t) = W_0 - 0.4 * C_0 * \alpha - v_M * \alpha_M * M_0 - v_{PW} * \alpha_M * M_0 + K * (0.0625 * C_0 * \alpha + v_{CS} * \alpha_M * M_0) \quad (11)$$

where K is water imbibed coefficient, v_{CS} is chemical shrinkage from per unit mass reacted mineral admixture. $0.0625 * C_0 * \alpha$ is chemical shrinkage of cement hydration, and $v_{CS} * \alpha_M * M_0$ is chemical shrinkage of mineral admixture reaction. Imbibed coefficient K relates to connectivity of pore spaces of concrete.

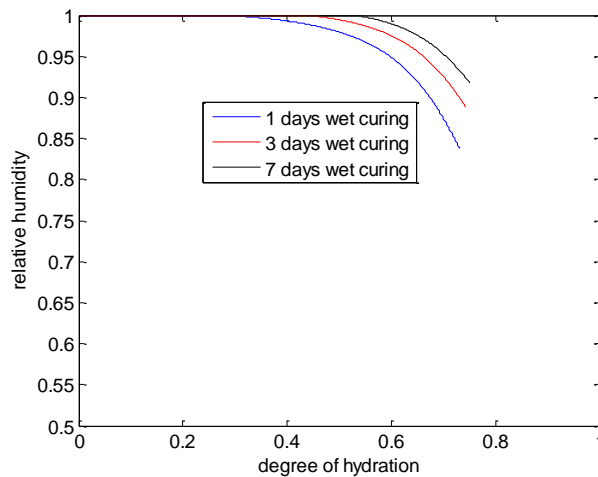
Figure 7 shows effect of wet curing periods on self-desiccation. With the increasing of wet curing periods, degree of hydration marginally increase (Figure 7-a), and self desiccation significantly decrease (Figure 7-b and Figure 7-c). Hence the extension of wet curing is effective to reduce self desiccation.



(7-a) degree of hydration



(7-b) RH as function of curing ages

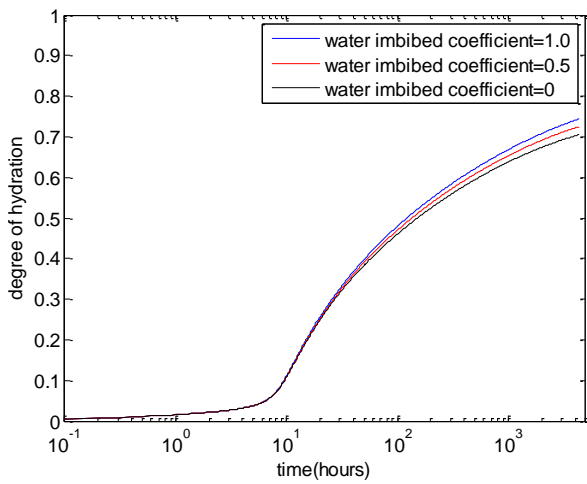


(7-c) RH as function of degree of hydration

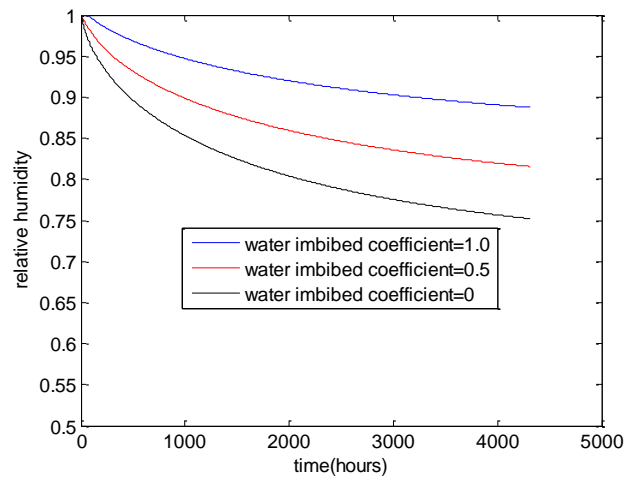
Figure 7. Effect of wet curing periods on self-desiccation ($w/b=0.3$, water imbibed coefficient=1.0)

Because high-strength concrete has a low water/cement ratio and dense microstructure, the moist-curing water from surround wet environment do not fully penetrate the concrete. The water imbibed coefficient varies between 0 and 1. Water imbibed coefficient $K = 1$ means that empty air space produced from chemical shrinkage can be fully filled with imbibed water. And Water imbibed coefficient $K = 0$ means that empty air space produced from chemical shrinkage can not be filled with imbibed water. Figure 8 shows the effects of

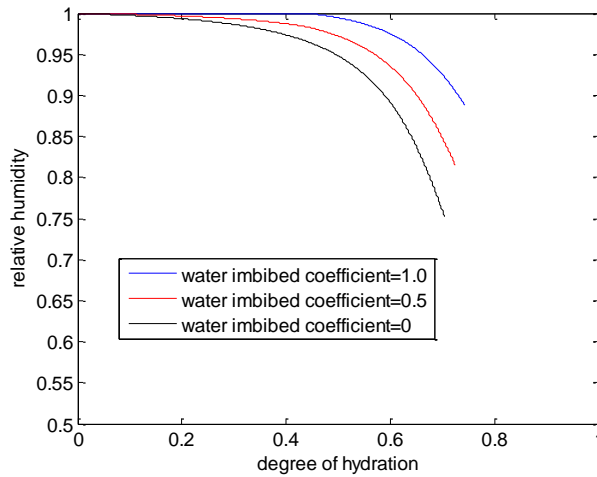
water imbibed coefficient K on self-desiccation. With the increasing of imbibed coefficient, degree of hydration marginally increase (Figure 8-a), and self desiccation significantly decrease (Figure 8-b and Figure 8-c). Hence the improvement of imbibed coefficient is effective to reduce self desiccation.



(8-a) degree of hydration



(8-b) RH as function of curing ages



(8-c) RH as function of degree of hydration

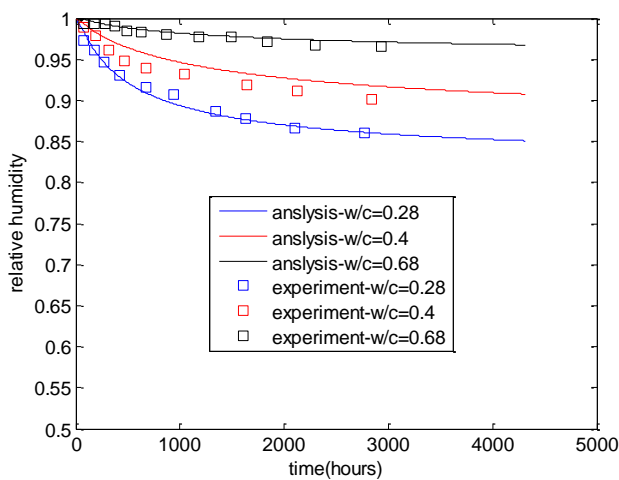
Figure 8. Effect of imbibed coefficient on self-desiccation ($w/b=0.3$)

Kim and Lee [2] studied self-desiccation in concrete with different mixing proportions and curing conditions. Concrete mixing proportions are shown in Table 1. Concrete specimens with three levels of compressive strength (water to cement ratios 0.28, 0.4, and 0.68) was used, and were moist-cured for 3 days or 28 days before the starting of self-desiccation tests. The curing temperature during moist curing and self-desiccation tests is 20°C. As shown in Figure 9-a and Figure 9-b, the analysis results generally agree with experimental results.

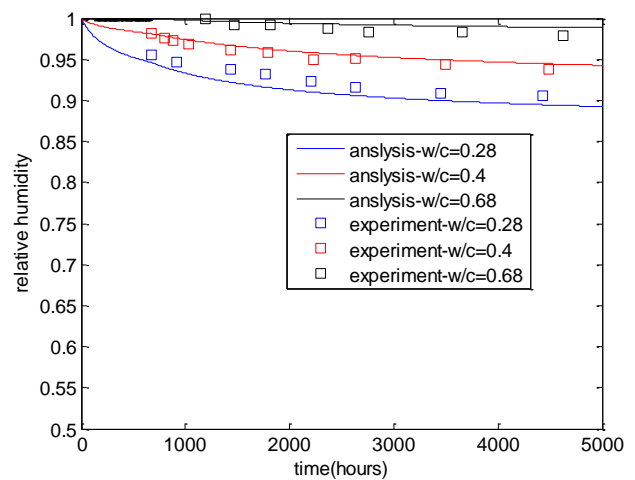
Extension of water curing period is effective to reduce self-desiccation. After initial moist curing, concrete with water to cement ratio 0.28 shows slightly relative humidity reduction. It means that extra water from moist curing can not fully penetrate the microstructure of concrete with a lower water to cement ratio. The proposed model is valid for concrete with different water to cement ratios and moist-curing periods.

Table 1. Mixing proportions of concrete

Specimen	Water to cement ratio	Water (kg/m ³)	Cement (kg/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)	Superplasticizer (cement*%)
High strength concrete	0.28	151	541	647	1055	2.0
Middle strength concrete	0.40	169	423	736	1016	0.5
Low strength concrete	0.68	210	310	782	955	-



(9-a) 3 days wet curing



(9-b) 28 days wet curing

Figure 9. Verification of proposed model

CONCLUSIONS

This paper presents a numerical procedure to analyze self-desiccation of high performance concrete.

Self desiccation model is combined with cement hydration model. By using cement hydration model, the reaction degree of binders, chemical shrinkage, capillary water, and gel water are calculated. Using a desorption isotherm consisting of capillary desorption isotherm and gel desorption isotherm, the self-desiccation of concrete are calculated. The effects of water to binder ratios, silica fume replacement ratios, fineness of cement, curing temperature, and curing conditions (sealed curing and wet curing) are considered in this study. The analyzed results agree with experiment results of concrete with different mixing proportions and curing methods. The analyzed results are valuable for concrete curing regime design and mitigating early-age autogenous crack in high performance concrete.

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