Modeling of Setting Behavior in Fresh Concrete considering Microstructure Formation

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ABSTRACT

In the analysis of early-age concrete behavior, the fresh concrete is considered as a structural element immediately after mixing. But for the activation of real structural behavior in the fresh concrete, the so-called setting time is necessary a few hours after the beginning of hydration reaction. In this paper, analysis on the setting behavior is carried out by proposing an analytical model based on the percolation theory as well as the expanding cluster model by defining the setting as a microstructure formation in fresh concrete. An experimental investigation is also carried out to show the influences of curing temperature, mineral admixtures and chemical admixture on setting behavior of fresh concrete. Finally, the analytical results using proposed model are compared with the experimental results for the sake of verification.

1. Introduction

In a conventional way of analyzing early-age concrete behavior, we usually consider fresh concrete as a structural element immediately after mixing. But for the activation of real structural behavior of fresh concrete, it takes some time after the beginning of hydration reaction. So, the very early-age deformations due to hydration heat and shrinkage that occur before the setting do not produce restraint stresses. In order to analyze the early-age concrete behavior more precisely, it is necessary to develop an analytical model which represents the setting characteristics in fresh concrete.

The setting characteristics of concrete is directly linked to hydration process, so the influencing factors of hydration reaction control the setting behavior of early-age concrete. Previous research indicates that the setting behavior of concrete is influenced by water/binder ratio, initial and curing temperature, type and dosage of mineral admixture and chemical admixture1). In this paper, we proposed an analytical model for setting characteristic, which considers these influencing factors based on the percolation theory and expanding cluster model. An experimental investigation was also performed to assess the influence of water/binder ratio, curing temperature, mineral admixtures and chemical admixture on setting behavior of early-age concrete. The experimental results were compared with the analytical results using the proposed analytical model for the sake of verification.

2. Modeling of setting time based on percolation theory and expanding cluster model

At present, some researchers define setting behavior based on the percolation theory, which explains birth, growth and linkage of internal microstructure of hydrating grains2). The isolated hydrating grains originated randomly in the volume build up out-layer cluster of each grain and

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expand to build up connection between them. The fraction of connection necessary to allow transition of a certain action is called the percolation threshold of that action. Garboczi and Bentz[3)] studied on the percolation threshold using digitally based three-dimensional simulation program that simulates the hydration process. From the study, they concluded that hydration degree at percolation threshold differs with different water-cement ratio but volume fraction of hydrates is constant regardless of mixture condition. In this study, the setting time is defined also based on percolation theory and the volume fraction of hydrate at the percolation threshold is considered to be invariable.

In order to derive an analytical setting behavior model, a microstructure development model is necessary to calculate the volume of hydrates at any given time. For that purpose, the so-called expanding cluster model based on degree of hydration proposed by Maekawa et al. is adopted[4)]. Figure 1 shows a schematic representation of the expanding cluster model. As shown in Figure 1, hydration product nucleated outside layer of original cement particle is increased as the hydration proceeds, then the thickness of the hydration product cluster is expanding. Let the average radius of cement particle is r_0, the maximum thickness of expanding cluster is $\delta_{\max}$ and the thickness of expanded cluster at a time is δ, then the volume ratio of the hydrates V_r at certain time can be calculated using Eqn.(1).

$$V_r = \frac{(r_0+\delta)^3 - r_0^3}{(r_0+\delta_{\max})^3} \tag{1}$$

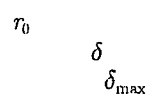

Figure 1. Expanding Cluster Model

The geometrical parameters r_0 and $\delta_{\max}$ can be obtained by stereological description of the initial state of mixture, and δ can be determined using mass compatibility of produced hydrates. By using the FE program which combines the aforementioned models[5)], the analysis of setting characteristic for fresh concrete are carried out.

As mentioned earlier, the percolation threshold is defined as the fraction of connection necessary to allow transition of certain action. Incase of final setting time, the percolation threshold is defined as a volume ratio of hydrates that allows load transition. In this study, the volume ratio of hydrates at the final setting time is defined as critical volume ratio. To determine the critical volume ratio, we compare the experimental results on final setting time with analytical results. Each final setting time for three different mix proportions as shown in Table 1 is obtained by test of ASTM C 403[6)], then volume ratio of hydrates at each final setting time, the critical volume ratio, is determined.

Table 1 Mix Proportions for Critical Volume Ratio

Water-cement ratio	Fine aggregate ratio	Unit weight (kg/m^3)			
		Cement	Water	Fine aggregate	Coarse aggregate
0.37	0.38	446	165	665	1085
0.47	0.42	351	165	767	1060
0.57	0.45	289	165	845	1032

The penetration resistance test results with time for three different mixtures are shown in Figure 2 and the comparison of both experimental and analytical results is shown in Table 2. As shown in Table 2, the volume ratios of hydrates at final setting time are between 0.13~0.14, while the degrees of hydration are between 0.15~0.21, which are relatively large variations. Thus, the critical volume ratio of hydrates is determined as a constant, 0.135. It is clear that the approach which defines the final setting time based on percolation theory is convenient than approach on degree of hydration.

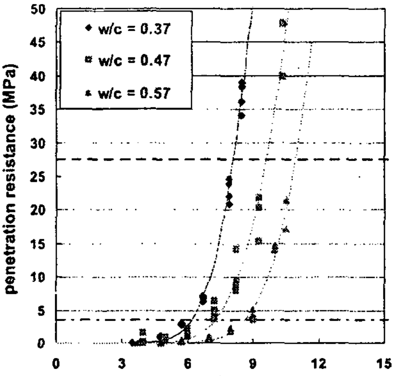

Figure 2. Setting behavior for three different mixtures

Table 2. Test and Analysis on Setting

w/c (%)	final setting time (experiment, hour)	analysis results at final setting time	
		volume ratio of hydration products	hydration degree
37	8.12	0.132	0.155
47	9.62	0.138	0.184
57	10.93	0.139	0.210

3. Verification of setting behavior model

An experimental investigation is also carried out to show the influence of mixture conditions. To investigate the influence of curing temperature on setting behavior, two mixtures of different W/C ratio (0.37 and 0.47) cured at 40℃ were tested. The influence of pozzolanic mineral admixture (fly ash, GGBFS and silica fume) on setting behavior was also investigated. Two different amounts of fly ash replacement (10% and 20% by cement mass), GGBFS replacement (30% and 50%) and silica fume replacement (5% and 10%) for the mixture of W/C ratio 0.47 were tested. Likewise, two different amounts of chemical admixture (superplasticizer) were evaluated (0.375% and 0.75% as a percentage of cement mass). Blain values of the fly ash, GGBFS and silica fume are 363 cm^2/kg, 434 cm^2/kg, 1600 cm^2/kg, respectively and a naphthalene type superplasticizer was used.

As curing temperature elevated from 20℃ to 40℃, the setting time is considerably shortened and the time gap between initial set and final set is also reduced. The observed acceleration in setting times due to higher curing temperature can be mainly attributed to the temperature dependency of hydration reaction. The replacement ratios of mineral admixtures become higher, the setting times are delayed. The retardation of setting time is due to replaced addition of relatively inactive mineral admixture. Silica fume, however, does not show clear retarding effect on setting behavior of concrete. Because the substitution ratio of silica fume is relatively low and the particle size of silica fume is small enough to accelerate the formation of interconnection between hydrating particles by filling effect, theretardation effect of silica fume originated from pozzolanic nature is diminished. Superplasticizer is the most effective retarder and the delay effect on setting time appears to be nonlinear with dosage of superplasticizer.

For the sake of verification, the analytical results using the proposed model are compared with the experimental results. Table 3 shows that the proposed setting behavior model can estimate well for different mixtures and curing conditions within about 4.5% error in average.

Table 3 Comparison of experimental and analytical results

setting time (hour)	cuing temperature		fly ash (w/c 0.47)		slag (w/c 0.47)		silica fume (w/c 0.47)		superplasticizer (w/c 0.37)	
	w/c 0.37	w/c 0.47	10%	20%	30%	50%	5%	10%	0.375%	0.75%
experiment	4.48	4.97	10.23	10.83	11.00	12.10	9.91	9.43	9.72	10.90
analysis	4.80	5.28	10.08	11.04	10.56	11.76	9.84	10.56	9.12	10.08
error (%)	7.14	6.24	1.47	1.94	4.00	2.81	0.71	12.00	6.17	0.92

4. Conclusion

In this paper, an analytical model for setting characteristic is proposed based on the percolation theory as well as the expanding cluster model by defining the setting as a microstructure development process in fresh concrete. Through the comparison of analytical results with test results on final setting time, a critical volume ratio of hydrates is determined. Experimental investigation on setting behavior is carried out to show the influence of curing temperature, mineral admixtures such as fly ash, GGBFS and silica fume, and chemical admixture along with analytical prediction. The investigation shows that high curing temperature accelerates the setting time and the mineral admixtures generally delay the setting time due to replacement ofcement with the mineral admixtures and the chemical admixture is the most effective retarder. The analytical predictions by proposed model show good agreement with experimental results. It can be considered that the proposed setting behavior model can be used for more accurate analysis of the early-age concrete behavior.

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