# Mix-Proportion and Mixing Procedure for Stable Entrained Air in Self-Compacting Concrete

# 論 文 内 容 の 要 旨

1. Introduction

Air-enhanced self-compacting concrete (air-SCC) is an improvement on SCC to reduce the unit cost by using entrained air working as ball bearing to enhance the self-compactability. By increasing the content of entrained air, fine aggregate volume and cement content can be reduced accordingly. In air-SCC, the water to cement ratio (W/C) was increased to 45% and the fine aggregate to mortar ratio (s/m) was increased to 55%. To enhance the self-compactability of air-SCC, air content was aimed to increase to 10%. With this target air content, it is indispensable to produce a stable system of air entrainment so that the loss of air content is prevented and the self-compactability is improved.

The objectives of this study are:

- to determine the critical size of air bubbles which harmfully affects the stability of air.
- to introduce an effective mixing method which is capable to produce a stable air entrainment system.
- to identify the required dosage of air entraining agent subjected to different mixing procedure on entraining coarse size air bubble.
- to verify the effect of viscosity due to different mixing procedure and mixing time on entraining coarse or fine size bubbles.
- to verify the air entrainment subjected to sufficient or shortage of air entraining agent.

2. Critical size of entrained air to stability of air volume at fresh stage

2.1 Purpose

The purpose of this chapter is to estimate the range of chord length of air bubbles which causes a harmful effect on the stability of air bubbles.

2.2 Hypothesis

Air bubbles with smaller size (higher internal pressure) are more stable than coarser size air bubbles (lower pressure). So, the mixture containing high content of coarse size air bubbles would be more likely to possess a poor stability of air. It is important to determine the critical size of air bubbles which could be harmful to the stability of air. Then the effective method to minimize or eliminate those harmful air bubbles will be indispensible to obtain adequate stability of air.

### 2.3 Experiment procedure

To determine the critical size of air bubbles, air distribution of mortar samples produced by different mixing procedure and mix-proportion were conducted by linear traverse method at hardened stage and by air void analyzer (AVA-3000) test method at fresh stage.

Linear traverse method consists of the determination of air volume of the concrete by summing the length traversed across air bubbles along a series of regularly spaced lines in the plane intersecting the sample. The significant of this method is to enable developing data to estimate the likelihood of damage due to cycling freezing and thawing or to explain why it has occurred. In this study, data generated from this test method will enable explaining the effect of different mixing procedure and different mix-proportion on the stability of air bubbles.

The AVA test method was developed to measure of air-void system of concrete or mortar at fresh. Before this invention, it is hard to fully understand the initial stage of air-void system which is required to assure that the target air entrainment is achieved. For this study, this test method is beneficial to fully understand the characteristics of the air-void system at fresh stage to be able to adjust the suitable mixing method and mix-proportion which encourage a finer system of air-voids and improve the stability of air bubbles.

### 2.4 Results

With linear traverse method, the correlation between stability of air and air volume of bubble size larger than 700μm at hardened stage was found with the highest value. The stability of air was found depend on the air volume of coarser size bubbles more than the smaller ones. Since the measurement with this method was done at hardened stage, there were air bubbles already escaped during hardening, thus the actual critical size of bubbles could be larger than 700μm.

With AVA test method, the relationship between the stability of air content of mortar at fresh stage at different bubbles size was evaluated. As the result, it was also found that the stability of air is more related to the content of coarser air bubbles than that of the smaller ones. The highest value of correction ($R^2$) of 0.93 was obtained with the chord length larger than 1000μm. This means that the higher the presence of air volume at chord length larger than 1000μm, the worse the stability of air could be occurred. This same result was also found in case of air distribution of self-compacting concrete.

## 3. Hypothesis: Required dosage of air entraining agent subject to mixing procedure resulting in coarse or fine air bubbles

### 3.1 Purpose

The purpose of this chapter is to clarify the effect of dosage of AE required on generating the air entrainment with different mixing procedure. Also it is to clarify the effect of dosage of AE in minimizing the volume of coarse size air bubbles which was found harmful to the stability of air in the previous chapter.

### 3.2 Hypothesis

It is known that AE was used to stabilize air entrainment system. With sufficient dosage of AE, finer air bubbles would be able to stay in the system for longer time. In contrary, with shortage of AE, those fine air bubbles which were entrained during mixing would unify and formed a larger size bubbles. This phenomenon would cause the increase in coarse size air volume provoking the damage to the stability of air.

The author expected that by mitigating the friction of a mixture before entraining air content may improve the stability of air entrainment system. The present of various types of chemical admixture in SCC caused a complicated situation to produce a stable system of air entrainment. Some studies have reported that with the present of superplasticizer (SP), higher dosage of AE was required to reach the same air content as the mix without SP. The present of these two admixtures may interrupt the action of one another resulting in lowering the quality of air entrainment and the workability of a mixture.

To propose an effective mixing method, it is indispensable to fully understand the mechanism of SP and AE. SP is a kind of water-reducing agent which works as cement dispersants through electro-steric repulsive force. Electro-steric dispersion is a combination of electrostatic dispersion and steric dispersion. This dispersion is created by the adsorption of the ions on cement particle, giving a slight negative charge as well as creating a layer on the surface of the particles. Air-entraining agent is a group of surfactants which reduces the surface tension at air-water interface. AEs help stabilizing the micro air bubbles formed during the mixing process. The hydrophobic end of AE (tail) is attracted to the air and the hydrophilic end (head, usually negatively charged) orients itself towards the water. This action form a water-repelling film on air bubbles and the negative charged disperse air bubbles from each other.

With the present of SP, the air content tends to be reduced. The negative charge keeps cement particles attached with air bubbles dispersing from each other and then reduces the friction of the mix and allows less space for the formation of air bubbles. When SP and AE are poured and mixed at the same, the mechanism of these two admixtures may become more complicated. To some level, the admixtures may disturb the effectiveness of each other resulting in both poor workability of a mixture and unstable air entrainment. By considering these phenomena, the author had proposed a hypothesis that by firstly introducing SP and mixing before introducing AE, is beneficial to allow SP to disperse the particles to an optimum level. Thereafter pouring and mixing AE, a lower initial air content may be obtained but with an improvement on stability of air entrainment.

### 3.3 Experiments

The first experiment in this chapter was to determine the most effective mixing method which is able to enhance the stability of air bubble as much as possible. Three main different mixing methods were conducted in this chapter. First, in simple method, the fine aggregate and the cement were firstly mixed for 30 seconds. Then the water, SP and AE were added and mixed at the same time. Second, in water dividing method, after mixing the cement and fine aggregate, the SP and first portion of water were firstly mixed. Then the AE and the rest portion of water were mixed. Third, in the last method, after mixing the cement and fine aggregate, the SP and all water were mixed prior to mixing AE.

Air distribution of mortar sample produced with different mixing method at different dosage of AE was evaluated. Air distribution of mortar produced with the increase dosage of SP and prolonging mixing with SP was tested to question the effect of different viscosity on entraining coarse size air bubbles. The verification will be done in the next chapter.

### 3.4. Results

It was found that the mixing method in which SP was added and mixed at first prior to adding of AE was effective in producing an adequate stability of air. At the same time, it was found that this mixing method (called effective method) entrained considerably lower content of air than that entrained by the simple mixing method.

The air distribution of mortar produced by the effective mixing method was found finer (through entraining less content of coarse size bubbles) than that produced by the simple method. With the effective mixing method, higher dosage of AE improved the fineness of air distribution by entraining higher volume of small size air bubbles and decreasing the volume of coarse size air bubbles. On the other hand, there was no improvement on fineness of air entrainment occurred with higher dosage of AE in case of method A since air volume at each size of bubbles was increased and the total air volume was increased dramatically.

## 4. Verification 1: Efficiency in entraining volume of air affected by viscosity subjected to mixing procedure

### 4.1 Purpose

The purpose of this chapter is to identify the effect of viscosity subjected to different mixing procedure on the formation of coarse size air bubbles. Clarification on the effect of different mixing method and mixing time enables minimizing the content of coarser size air bubbles thus improving the stability of air.

### 4.2 Hypothesis

The viscosity of the mixture during mixing could be a determinant factor for fineness of air distribution. Even though higher viscosity of mixture could reduce the rate of escaping air bubbles, if the presence of coarser size bubbles was high (move faster than the smaller ones), the stability of would not be able to improved neither. Since the target of this study is to ensure the stability of air, the finer the air system is preferable.

### 4.3 Results

The effective mixing method produced a lower viscosity mixture than that produced by the simple mixing method. Lower viscosity of mixture entrained lowered air volume but at the same time eliminating the volume of coarse size air bubbles which is beneficial in improving the stability of air. With effective mixing method (method B and C), the air volume could be increased through prolonging mixing time with AE.

With mixing method B and C, longer mixing time with AE entrained finer system of air bubbles through increasing the air volume of fine size bubbles and more likely decreasing the air volume of coarse size bubbles.

On the other hand, longer mixing time conducted with mixing method A entrained higher volume of only air bubbles size larger than 1000μm causing no improvement on fineness of air bubbles and harmfully decreasing the stability of air.

## 5. Verification 2: Entraining fine or coarse air bubbles subjected to dosage of air entraining agent

### 5.1 Purpose

The purpose of this chapter is to clarify the effect of dosage of AE on entraining coarse or fine size air bubbles.

### 5.2 Hypothesis

It is known that AE was used to stabilize air entrainment system. With sufficient dosage of AE, finer air bubbles would be able to stay in the system for longer time. In contrary, with shortage of AE, those fine air bubbles which were entrained during mixing would unify and formed a larger size bubbles. This phenomenon would cause the increase in coarse size air volume provoking the damage to the stability of air.

### 5.3 Results

Sufficient dosage of AE could eliminate coarse size air bubbles while increasing the air volume of fine size bubbles. Shortage of AE resulted in the faster unification of fine size air bubbles thus increasing the air volume of coarse size air bubbles.

With the effective mixing method, usually sufficient dosage of AE was accompanied to achieve target air content. Longer mixing time and increasing AE dosage at the same could increase higher content of finer size air bubbles while cause no increase of air volume at the coarser size.

## 6. Conclusion

1) Higher content of coarse size air bubbles induces higher loss of air content in 2 hours and during hardening. The critical chord length of air void was found larger than 1000μm.
2) The effective mixing method for enable producing adequate stability of air was the method in which SP was introduced with water and mixed ahead of mixing AE. With effective mixing method, prolonging mixing time with AE could enable decreasing the coarse size air bubble and at the same time entraining more air bubbles with a finer size. The viscosity of the effective mixing method is lower than the simple mixing method.
3) With the effective mixing method, longer mixing time with AE in accompanied with higher dosage of AE increased higher content of fine size air bubbles without increasing coarse size air volume.
4) The effective mixing method required significantly higher dosage of AE to reach same target air volume comparing to the simple mixing method. Sufficient dosage of AE could eliminate coarse size air content. With shortage of AE, the unification between fine size air bubbles occurred faster and formed larger air volume at coarse size bubbles.