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Improving the stability of entrained air in self-compacting concrete by optimizing the mix viscosity and air entraining agent dosage

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HIGHLIGHTS

- Lower viscosity resulted in less coarse air bubbles.
- Higher dosage of AE agent reduced coarse air volume.
- Longer mixing time increased fine air bubbles as long as its upper limit volume is not reached.

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ABSTRACT

The purpose of this study is to clarify the role of mixing procedure and air entraining agent (AE) on the entrained volume of fine and coarse air bubbles with the aim of improving the stability of entrained air in self-compacting concrete (SCC). Experiments were conducted in which the air bubbles size distribution of fresh mortars was measured with an air-void analyzer (AVA). Critical size of air bubble was defined as the size below which the bubble volume remains stable as time pass. This critical size, defined in terms of chord length, was found to be 500 μm from the correlation between the volume of larger bubbles and the reduction in volume two hours after mixing. A lower mortar viscosity, obtained using a mixing procedure in which water additions were divided, reduced the total volume of both fine and coarse air bubbles. With a higher dosage of AE, a higher volume of fine air bubbles and a lower volume of coarse air bubbles were entrained. An upper limit volume of fine air was defined as the maximum volume of fine air bubbles entrained with a longer mixing time. This upper limit is proportional to the AE dosage multiplied by the funnel speed of the mortar as an index of viscosity.

1. Introduction

1.1. Background

Self-compacting concrete (SCC) was first proposed by *Okamura* in 1986 as a means to achieve durable concrete that is independent of the quality of the construction workers. A fundamental study on the workability of SCC and its development were then conducted by *Okamura*, *Maekawa*, and *Ozawa* [1–3]. Air-enhanced self-compacting concrete (air-SCC) was developed as part of this study to increase reliability in the handling of normal strength concrete and increase the accessibility of SCC at various construction sites. Briefly, air-SCC is a normal strength concrete with a self-compacting property. Compared with conventional SCC, the water-to-cement ratio (W/C) was increased to 45% by weight, the fine aggregate-to-mortar ratio (s/m) was increased to 55% by volume and the self-compactability was enhanced by increasing the air volume to about 10%. Examples of mix-proportions for ordinary concrete, conventional SCC and air-SCC are shown in Table 1.

The self-compactability of SCC, as characterized by a high flowability property, means that obtaining adequate air entrainment is a difficult task [4–6]. In higher flowability concrete, air bubbles could move more freely thus increasing the rate of coalescence between air bubbles or collapse of air bubbles. According to *Sovannsathya* [7,8], the stability of entrained air in the mortar of air-SCC can be effectively improved by modifying the mixing procedure. Using this modified mixing procedure, there is a possibility of obtaining further improvement in the entrainment of fine air bubbles by considering other parameters.

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Table 1
Examples of mix-proportions for different types of concrete.

	Air (%)	W/C (%)	s/m (%)	(kg/m^3 of concrete volume)			
				Water*	Cement	Fine aggregate	Coarse aggregate
Ordinary concrete	5	55	50	181	329	764	1018
Conventional SCC	5	30	40	194	646	713	764
Air-SCC	10	45	55	166	369	929	724

* including superplasticizer and air-entraining agent.

1.2. Objective

The objective of this study is to clarify the combined roles of mixing procedure and AE dosage on the entrained volume of fine and coarse air bubbles in terms of air entrainment stability. The influence of AE dosage and viscosity differences (arising from different mixing procedures), on the ability to reach a defined upper limit volume of fine air bubbles during the mixing time is also to be clarified.

2. Distingusihing fine and coarse air bubbles

In this study, coarse and fine air bubbles in concrete are distinguished by defining a critical size of bubble, above which air bubbles easily escape either by collapsing in the matrix or floating upward then fading away. According to *Sovannsathya* [9,10], air bubbles with chord length greater than 1000 μm are the most harmful to the stability of entrained air. Bubbles in this category are ready to escape by one of these mechanisms. The study also showed that unification of air bubbles must also be considered, since smaller air bubbles join together to form a larger bubble as time pass. It was found that, due to air bubbles joining in this way, the partial volume of air bubbles with a chord length in the range 500–1000 μm also contributed negatively to entrained air stability. Thus, to ensure air stability as much as to simplify the analysis, the critical size of air bubble is defined as one with a chord length of more than 500 μm. The effect of the volume of air bubbles with a chord length exceeding 1000 μm, 500 μm and 300 μm on the stability of entrained air over a period of 2 h is shown in Fig. 1.

3. Effect of mix viscosity on entrained volume of coarse or fine bubbles

3.1. Hypothesis

The viscosity of the mixture during the mixing process to entrain air bubbles could be a determinant of the fineness of the air bubble size distribution. Even though a mixture of higher viscosity might reduce the rate at which air bubbles escape, the stability of the entrained air would not be improved if proportion of coarse bubbles were high. Since the aim of this study is improving the stability of the entrained air, a finer air system is preferable. It is better to initially entrain finer bubbles that enhance stability rather than encourage the coarser bubbles that might result from a high viscosity mixture. The expected effect of viscosity on the entrained volume of coarse or fine bubbles according to this hypothesis is shown in Fig. 2.

3.2. Experiment

3.2.1. Materials for mortar experiments

Mortar samples used in this study were produced using ordinary Portland cement with a specific gravity of 3.15 g/cm^3, crushed limestone sand as the fine aggregate, a polycarboxylic-based containing viscosity agent for the superplasticizer (SP) and an alkyl ether-based anionic surfactant for the AE. The properties of these materials are given in Table 2.

3.2.2. Mixing procedure

Different mixing procedures were used since modification of the mixing procedure had been found to effectively improve the stability of entrained air [7,8]. The mortar mixture in this study was produced with both water-reducing admixture and air-entraining agent. With the presence of both admixtures, the order of adding admixture for mixing was critical. It is widely known that if both types of admixture are added for mixing at the same time, the interaction between these admixtures could interfere the effectiveness of one another. In the adjustment on the mixing procedure of this study, SP was considered to introduce before AE so that the mortar mixture was less viscous that could minimize the presence of coarse air bubbles. The two mixing procedures illustrated in Fig. 3 were implemented. Mortar mixer used in this study has a rotation speed of 140 ± 5 rmp.

Mixing procedure A was a simple one in which the cement and fine aggregate were first mixed together for 30 s, then all the mixing water, SP and AE were added and mixed for Y minutes. In mixing procedure B, after mixing the cement and fine aggregate together for 30 s, the first portion of water and the SP were added and mixed for X minutes. Finally, the rest of the water and the AE were added and mixed for Y minutes. The first portion of water was adjusted such that W/C at the moment of SP addition was 30%. The mixing time with AE (Y) in both mixing procedures was chosen to be 2 min in all cases and the mixing time with SP (X) in the case of mixing procedure B was set at 1 min.

3.2.3. Air-void analyzer (AVA-3000)

3.2.3.1. Significance of test method. The air size distribution of the mortar samples was measured at the fresh stage using an air-void analyzer (AVA), which enabled the understanding of the air distribution in the fresh mortar. Prior to development of the AVA, it was hard to fully understand the air-void system at this stage, though it is important for adjusting the target air entrainment. In this study, the AVA test method was beneficial to fully understand the characteristics of the air-void system and thus verify the effect of viscosity and AE agent dosage more precisely.

3.2.3.2. Mechanism of measurement. The AVA method entails expelling all air bubbles present in a given mortar or concrete sample, collecting the expelled bubbles, and recording their quantities and size distribution. The sample is placed in a viscous release liquid and stirred using a magnet to release all air bubbles. With careful control of the liquid viscosity, the air bubbles retain their original size without coalescing or disintegrating into smaller bubbles. According to Stokes law, the speed at which air voids rise through a liquid is dependent on their size. The viscosity of the release liquid slows down the initial rise of the bubbles, thereby providing a measurable separation in arrival time at the top of the column of bubbles of different sizes.