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Mechanisms of air entrainment in concrete

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Abstract

The advent of air-entraining agents is probably one of the most important technological advances in construction in the last century. It has been widely used to improve the freeze–thaw resistance of concrete, and to a lesser extent, the workability of concrete. Despite the overall successful application of air-entraining agents in concrete, problems in field concrete are not uncommon. The ability to consistently obtain target air-void systems in concrete is not trivial, and changes in raw materials, processing, or construction methods may significantly impact air entrainment. To address these potential problems in the field, a sound understanding of the mechanisms of air entrainment is essential. This paper attempts to synthesize available literature and field experience and provide a framework for understanding the fundamental aspects of air entrainment in concrete. Various parameters and influencing factors, such as concrete temperature, the physical and chemical characteristics of constituent materials, and mixing and placing techniques, are discussed.

Keywords: Adsorption; Air-entraining admixture; Air content; Stability; Temperature

1. Introduction

Ever since air entrainment was first discovered (by accident) in the mid-1930s, the concept of air-entrained concrete has become a rule, and not the exception in cold-climate concreting. Discovered by chance when a grinding aid used to enhance cement grinding ended up chemically entraining air in concrete and improving frost resistance in the field, air-entraining agents have had years of success in improving resistance to freezing and thawing damage (due to both internal distress and salt scaling) [1]. However, this success has not come without some turmoil as even today concrete producers wrestle with controlling air content in concrete, and the list of factors affecting air entrainment [e.g., temperature, cement chemistry, and supplementary cementing materials (SCMs)]. To fully understand the complexities of air entrainment, and more importantly, to apply this in practice, the mechanisms of air entrainment must first be understood.

Research has been devoted to the development of air-entraining admixtures (AEAs), the study of factors affecting the air-void system, and the correlations between air-void system and the corresponding freeze–thaw resistance. Mielenz et al. [2] discussed in detail the origins and evolution of the air-void system in concrete. Powers developed the concept of spacing factor of air voids, and this approach has been widely accepted to ensure the freeze–thaw resistance of concrete [3,4]. Zhang [5] studied the effects of different types of fly ashes and their dosages on the volume of air entrained, stability of air bubbles, and air loss with time with the use of different AEAs. The majority of the research has been placed on the practical aspects of air entrainment, with only slight emphasis on mechanisms of forming and stabilizing air bubbles in concrete. Bruere [6] discussed factors affecting the air entrainment in cement and silica pastes. Fagerlund [7] proposed three mechanisms that could lead to air-void instability in fresh concrete. Powers [8] also discussed in detail the process of air entrainment and various influential factors, although Powers did not address directly the complex chemical aspects of the bubble forming and stabilizing processes.

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Although air entrainment is a common practice, failure due to inadequate air entrainment is still common and has been reported in the literature [9]. A fundamental shortcoming of air entrainment today is that only total air content is typically specified, although as Powers [4] pointed out, air-void size and distribution contribute more to frost resistance. However, the extreme difficulty of obtaining the bubble size distribution in fresh concrete makes it only practical to measure the total air content as a quality control measure. The essential characteristics of air-void systems are typically only evaluated when called for by a specification (which is rare) or as a result of less than stellar field performance. These analyses of air-void size and distribution are almost always performed on hardened concrete specimens, although a reasonable index of air bubble size and distribution can be gleaned from fresh concrete using available commercial equipment.

Given that there are still problems in the field in properly entraining air and that so many factors influence air in concrete, it is imperative to understand how bubbles are formed and what makes them stable, unstable, or somewhere in between. The remainder of this paper discusses the factors that most affect air entrainment from a mechanistic perspective and is based on a synthesis of published literature and field experience.

2. Formation and stabilization of air voids in fresh concrete

Chemically entraining air in concrete is difficult to be categorized in the sense of a conventional chemical process. It can be viewed as an emulsion of air in the aggregate–cement–water system or foam formation in the liquid phase and retained by the solid network, or both. This paper focuses on the overall air entraining process and no distinct classification will be made between emulsion and foaming. Similar to foams, air bubble formation and stability in fresh concrete should be considered as two separate processes that are equally important for the air-void system in hardened concrete. These two phenomena are discussed below.

Dodson [10] presented a comprehensive review of air entrainment in concrete, and Powers [8] described how the two primary processes in the mixing action generate air in concrete. One process proposed by Powers is infolding of air by a vortex action, like stirring a liquid. The other process is a so-called *three-dimensional screen* formed by the fine aggregates when the mass falls and cascades onto itself during mixing. Mielenz et al. [2] proposed four origins of air in concrete, which include air already contained in the system and air entrapped during mixing. Reviewing past literature on air entrainment revealed that it is clearly an extremely complex process, which is affected by many factors, including the mixing process, concrete mixture proportioning, fine and coarse aggregates characteristics, physical and chemical properties of portland cement, water amount and quality, dosage and properties of air-entraining agent, other chemical admixtures and SCMs, and a range of other parameters. Because it is such a complex phenomenon, the usefulness of any quantitative model to predict the air-void system characteristics is questionable. As such, the aim and approach of this paper are more qualitative, although some experimental data are cited.

Air bubbles in fresh concrete are inherently unstable. The interfaces between the dispersed air and the surrounding matrix contain free surface energy, and the thermodynamic tendency is to reduce the interfacial surface areas. Thus, all air bubbles have a lifetime (persistence). If concrete setting is severely retarded, lack of small air bubbles in hardened concrete may be expected, which is detrimental to the freeze–thaw resistance of concrete. From the point of foam instability, three fundamental physical mechanisms may lead to the collapse of air bubbles [11]:

1. Diffusion of air from a bubble (small, higher internal pressure) to a larger one (lower internal pressure) or into the bulk gas (or solution) surrounding the foam;
2. Bubble coalescence due to capillary flow leading to rupture of the lamellar film between the adjacent bubbles (usually slower than mechanism 1 and occurs even in stabilized system);
3. Rapid hydrodynamic drainage of liquid between bubbles leading to rapid collapse.

Because of the mechanisms behind the instability shown above, pure liquid cannot form stable air bubbles. For foams to be useful, they must have a reasonably long lifetime that is related to one or more stabilization mechanisms. The use of AEAs in concrete is a classic example of one of the applications of emulsion and foaming technology.

The three mechanisms of air-void instability in concrete described by Fagerlund [7] can be categorized in mechanism 1 listed above. Mechanism 2 discussed above can occur in fresh concrete as the vibration from consolidation may force air bubbles to come into contact and form a larger one. Mechanism 3 is not likely in fresh concrete because air bubbles in fresh concrete are immersed in water. Note that for a given air content in concrete, the larger the air-void diameter, the larger the spacing factor and specific surface area, and the lower the freeze–thaw resistance. Similar to emulsion stability, one can argue that physical agitation, like shearing (mixing) and rapid agitation (vibration), may also lead to the loss of air in concrete [12].

The hydration of portland cement is a complex and continuous process, and the rate changes with time. The mixing water surrounding air bubbles is continuously changing in solutes and concentrations. Cations (Ca^{2+}, Al^{3+}, Na^{+}, and K^{+}) and anions (OH^{-} and SO_4^{2-}) show their presence in liquid phase and some of them may have high amounts at a certain period of time. These ions can affect the entraining and foaming ability and persistence of a surfactant system, positively or negatively. Fresh concrete is