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Effect of air entrainment on shrinkage of blended cements concretes

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HIGHLIGHTS

- Shrinkage of air entrained (AE) concretes was higher than that of non AE concretes.
- Increase in shrinkage of concretes with increasing content of air voids was observed.
- Higher shrinkage might be due to air voids and porous air void–paste interface.
- Interconnection and overlapping of interfaces increased vapour diffusion and shrinkage.
- Bigger volume of cement paste in AE concrete may also increase shrinkage strains.

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ABSTRACT

Shrinkage strains of air-entrained (AE) concretes were bigger than strains of non-air-entrained concretes made with the same cements. The results clearly showed an increase in strains with increasing content of air voids, regardless of cement type. Higher shrinkage strains of AE concretes may be most probably related to their microstructure of complex porosity and in particular, to porous cement paste adjacent to air void. Occurrence of air void–cement paste interfacial transition zones of higher porosity as well as their overlapping and interconnection may increase vapour diffusion accelerating moisture loss and drying shrinkage. Another likely reason for shrinkage increase may be increase in the volume of cement paste and decrease in the volume of aggregate in AE concrete.

1. Introduction

Shrinkage is a complex process which involves a lot of summatively overlapping factors. Shrinkage of cement paste is a result of a decrease in its volume during the hydration and drying of cement. During cement hydration, water and cement phases are substrates whose volume is bigger than that of the hydration products. This decrease in volume is observed before and during cement setting and is known as a chemical shrinkage or contraction [1]. The primary driving force for shrinkage is capillary tension in the pores, occurrence of disjoining pressure and changes in the tension of solid gel molecules [2]. Concrete shrinkage is also influenced by the aging of cement paste. The polymerization reactions that constitute aging increase the stiffness (modulus) of the paste. The monomeric molecule of C—S—H liberates a water molecule whereby Si—O—Si bonds are formed. This mechanism of condensation densifies the gel and it explains why young (unaged) pastes exhibit irreversible shrinkage [3].

Irrespective of chemical and plastic shrinkage of early-age concrete, the total shrinkage may be, in the simplest way, divided into autogenous shrinkage and drying shrinkage. Autogenous shrinkage is uniform and isotropic and takes place in the entire volume. When concrete stiffens due to hardening of the cement paste, autogenous shrinkage is initiated [2]. The unhydrated cement absorbs water from capillary pores and nanopores for further hydration. Then, the self-desiccation follows and autogenous shrinkage occurs which in turn develops until hydration stops [4]. Unlike ordinary concretes, low *w*/*c* high performance concretes (HPC) made with bulk amount of cement show much more autogenous shrinkage due to shortage of capillary water necessary for cement hydration.

Replacement of cement with limestone powder (LP) and fly ash (FA) may decrease total shrinkage and its rate and, as a result, reduce the probability of short-time concrete cracking [5]. It was also observed that drying shrinkage lessened with the use of blast furnace slag (BFS), FA and metakaolinite [6]. However, there is no

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consensus that replacing part of cement with BFS decreases every type of shrinkage [7]. The results demonstrated that partial replacement of 50% and 70% of white Portland cement with slag reduced the total shrinkage by as much as about 25% and 40%, respectively. The quantification separately of autogenous and drying shrinkage of natural pozzolan, limestone and BFS cement mortar showed a very large – above 50% – decrease in autogenous shrinkage of mortar by replacement of 50% of cement with BFS [8]. Although BFS cement mortar showed higher drying shrinkage, its total shrinkage was still the smallest. Other test results showed that BFS cement concrete exhibited higher autogenous shrinkage than ordinary portland cement (OPC) concrete and that the higher the BFS content, the higher the autogenous shrinkage [9]. FA can reduce the shrinkage, and silica fume can increase the shrinkage, and the effect of BFS may be between the two mentioned [10]. Not all quoted test results on shrinkage of blended cement concretes are consistent. However, while evaluating the effect of mineral additives on shrinkage, it is important to take into account the specific surface of the additives and their relative content because a very large specific surface of the additive compared to OPC may increase shrinkage strain in the same way as the silica fume does. Questions arise, though, what the effect of air entrainment on shrinkage of blended cement concretes might be and whether the mineral additives could decrease shrinkage of AE concrete. It should be borne in mind that the more air-entraining agent (AEA) is needed for air-entraining blended cement concretes the larger mineral additive content (BFS, LP or FA) in concrete is. Moreover, it is more difficult to obtain proper features and arrangement of air voids in blended cement concretes compared to OPC [11].

Capillary porosity and capillary pore diameter distribution related to *w*/*c* ratio undeniably belong to main factors affecting shrinkage. However, while considering and investigating shrinkage of concrete containing air voids, one has to focus on the fact that they are connected with capillary pores and interconnected through capillary pores, too, which are the main path of moisture transport in the hardened paste of AE concrete. The entrained air voids can increase or decrease bulk transport properties depending on the transport mechanism under consideration [12]. Influence of air voids on transport properties suggests also possibility of their influence on shrinkage.

The drying shrinkage develops from the surface into concrete, just as moisture begins to leave the paste. The drying rate and shrinkage rate are not uniform since at the onset of drying their rate is relatively fast, but it gradually decreases with time given that under nearly saturated conditions both bulk water and vapour fluxes participate in moisture transport [13]. However, moisture movement in concrete in the form of vapour flux is dominant when pore-relative humidity is within the range of 15–95%. Then vapour flux is governed by vapour diffusion in unsaturated pore space [14]. That is why it is possible and favourable to describe moisture transport in concrete using diffusivity. Jafarifar et al. [15] determined that there exists a relationship between moisture diffusivity and moisture content of the unsaturated concretes and a relationship between free shrinkage and moisture loss. This, in turn, indicates that the shrinkage strains of unsaturated concrete are consistent with moisture diffusivity.

Since concrete contains 25–35% of cement paste in its volume and all air voids reside in cement paste, the volume of cement paste is usually increased by about 5–15% when, for instance, the entrained air content is equal to 3–6% of concrete volume. Thus, the occurrence of entrained air as a new, not insignificant fraction of cement paste volume may affect the shrinkage of concrete, all the more so that according to a known rule for ordinary and high performance concretes shrinkage is proportional to content of cement paste in concrete mix [16].

Due to air entrainment, the microstructure of hardened concrete is more heterogeneous because new fractions occur in it. Rashed and Williamson [17] have identified two distinct features to air voids: a shell to the air void surface and an interfacial transition zone between this shell and the bulk cement paste. The shell appears to be made up of small (1–5 μm) mineral particles [18]. Whereas, Ley et al. [19] showed that air void surface is made of C—S—H phase, with calcium/silicon ratio equal only to 1.1. For a bulk OPC paste, the ratio is 1.5. Due to the presence of water-rich fresh paste containing lower cement content around the air voids interfacial paste has higher initial *w*/*c* ratio compared to bulk paste farther away from the interface. The width of the interface zone adjacent to the shell is around 30 μm from its surface [12]. In general, it appears that the air void–paste interface is similar to aggregate–cement paste interfacial transition zone whose width is 20–50 μm. However, no precipitation of calcium hydroxide was observed at the air void–paste interface [18]. In extensive research of the microstructure in AE concretes and mass transport properties Wong et al. [12] stated that the porosity near the air void boundary is about 2–3 times that of the bulk paste and that air entrainment increases gaseous diffusivity and permeability by up to a factor of 2–3 in case of the highest air contents. Interfacial paste of porous microstructure occupies a large part of cement paste volume. The air void interfaces can overlap and interconnect. Therefore, the occurrence of air voids and related to them numerous changes in microstructure of AE concrete cannot be neutral for its properties.

Combining the conclusions based on AE concrete transport property research with shrinkage and concrete transport properties, certain relationships between drying shrinkage of AE concretes and vapour diffusivity can be observed. In AE concretes, gaseous diffusivity increases as the entrained air content grows. This, in turn, could suggest that air entrainment may result in accelerating vapour flux as well as affect water loss and shrinkage strains due to increased diffusivity. Moisture transport in AE concretes is more complex, as they have a wide variety of pore structures, permeable air voids and higher porosity of interfacial transition zone around air voids. Therefore, a certain effect of air entrainment on shrinkage strains of concretes is probable.

Though most shrinkage types of concrete containing a large variety of cements, aggregates and additives were thoroughly tested, a few observation and test results about the range of shrinkage of AE concrete have been published. According to scant data, the air entrainment of OPC concrete should not have any influence on its shrinkage. Fagerlund [20], when testing AE concrete properties, concluded that air entrainment does not affect shrinkage of OPC concretes. Also Keene [21], quoted by Neville [16], showed that concrete shrinkage is independent on air entrainment. There are in fact none for blended cement concretes. Therefore, an attempt was made to investigate the shrinkage of AE concretes manufactured from blended cements.

2. Experimental procedure

2.1. Aim and scope of the experiment

The aim of this study has been to investigate long-term shrinkage strains of air-entrained and non-air-entrained concretes to find the influence of entrained air voids. Concretes made with the use of several cements have been tested to determine whether mineral additives replacing part of OPC alter shrinkage strains of AE concretes as in the case of ordinary concretes. The aim has been also to identify the effect of increase in content of air voids on shrinkage strains of BFS cement and OPC concretes. Scanning electron microscopy (SEM) has been used to determine how the microstructure of air-entrained concrete can influence shrinkage strains. The effect of air entrainment on different strains has been also considered in relation to the content of cement paste in concrete containing various air volume.