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Effect of entrained air voids on the microstructure and mass transport properties of concrete

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ABSTRACT

The effects of entrained air on microstructure and transport properties of concrete with up to 11.5% air at different w/c ratios, curing and conditioning regimes were investigated. It was found that air voids disrupt the packing of cement and increase the heterogeneity of the microstructure. The width of the affected interface is around 30 μm. Gaseous diffusivity and permeability are increased by up to a factor of 2–3 at the highest air contents. This effect is similar to that due to increasing w/c ratio from 0.35 to 0.50 when samples are conditioned at 52% r.h or 50 °C. The effect on sorptivity is less consistent, while the effect on electrical conductivity is influenced by the moisture condition of the air voids. It is estimated that every 1% increase in air content increases transport by 10% or decreases it by 4%, depending on whether the air voids act as conductors or insulators.

1. Introduction

A typical concrete contains around 1-2% vol. of air voids that are inadvertently entrapped because of incomplete compaction. Air voids may also be deliberately incorporated by means of a suitable surfactant, i.e. an air entraining admixture. It is well established that air entrainment enhances the resistance of concrete to damage by repeated exposure to freeze-thaw cycles and salt scaling, by providing a system of discrete, small and closely spaced spherical voids that are well dispersed throughout the cement paste. The size of the entrained air voids is generally between ten and hundreds of microns. To ensure adequate frost protection, the spacing of the air voids should be smaller than a critical distance, typically 200–250 μm [1,2]. However, for simplicity and convenience, most standards prescribe the total air content by assuming that the spacing factor is inversely proportional to air content. For example, the recommended air content according to ACI 201.2R-01 [3] ranges from 3–7.5% depending on the maximum aggregate size and severity of the exposure, with a tolerance of ± 1.5% allowed for field concretes. The volume and size of the entrained air voids depend on many factors, including the type and amount of air-entraining agent, materials and mix composition, mixing and placing techniques. These issues and concepts relating to freeze-thaw damage and the beneficial effects of air entrainment have been reviewed elsewhere [2–5].

Because concrete contains around 65–75% vol. aggregate and all of the air voids reside in the cement paste, a small amount of air entrainment causes a significant change to the microstructure of the paste, and to its pore structure in particular. This in turn may have a significant effect on the properties of the hardened concrete. A well known example is strength loss that accompanies air entrainment. As a general rule of thumb, one-percentage increase in air content results in about 5% decrease in the compressive strength of concretes at equal water-to-cement (w/c) ratios. However, a more significant reduction in strength has been reported particularly when the air avoids cluster at the aggregate-paste interface [6,7]. Air entrainment also increases workability, improves consistency and reduces the bleeding and segregation tendency of fresh concrete [2,5].

Whereas there is an extensive body of work on characterising the air void system and determining its requirements for frost protection, very little research has been carried out on understanding the effects of entrained air on other aspects of hardened concrete such as mass transport processes and resistance to other forms of deterioration. Air voids are penetrable, but because they appear isolated in the microstructure and do not form a continuous flow channel, they are often assumed to make little or no contribution to the bulk transport properties of concrete. Thus, air voids are treated as inert inclusions similar to aggregate particles. Air voids may disturb the packing of cement grains and the distribution of porosity, but this effect could be negligible due to their small size relative to aggregates. Some studies suggest that air entrainment decreases the permeability of concrete, but this is often a result of a lower w/c ratio in the air-entrained mixes to take advantage of its improved workability [2,8]. Increasing the air content is accompanied by a change in other variables, such as the cement and aggregate content, that may have a larger influence on transport. For example, increasing the air content decreases the aggregate content if the cement content and effective w/c ratio are

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held constant, As such, it may be difficult to isolate the actual contribution of the entrained air voids.

The air voids may be empty or water-filled, depending on the exposure history of the concrete, and this has a significant influence on measured transport properties. For example, in McCarter et al. [9], the electrical resistivity of OPC concretes with 1:2:4 mix proportions, w/c ratio 0.8 and entrained air up to 16% was continuously monitored with wet curing from 24 hrs up to 80 days. It was found that electrical resistivity increased significantly with air content and the study concluded that air voids behave as non-conducting particles in a way similar to aggregates. However, in another study, Toutanji [10] measured the AASHTO T277 rapid chloride permeability (RCP) of concrete containing 2-15% entrained air and 0-20% silica fume at w/c ratio 0.41. Samples were cured at 100% r.h. and 22 °C for 7 days then dried at 30% r.h. and 28 °C up to the age of 35 days. The results show that air entrainment increases the RCP values significantly and because the RCP is a measure of electrical conductivity, this finding would seem to contradict that of McCarter et al. [9]. A probable explanation for the inconsistency is that the samples in Toutanji [10] were vacuum saturated prior to testing as per AASHTO T277 recommendations [11], and thus the air voids were water-filled and able to participate in electrical conduction.

The aim of this study is to carry out a systematic investigation into the influence of entrained air voids on the microstructure and bulk transport properties of concrete under saturated and non-saturated conditions. Several transport mechanisms are examined, because the influence of entrained air on each may not be the same. Understanding how the microstructure influences mass transport properties is vital for the development of more durable materials and accurate service-life prediction models. In order to model mass transport properties, it is necessary to identify the phases where flow predominates. Also, mass transport tests are increasingly being used as performance and durability indicators, thus it is essential to understand how air entrainment can influence test results.

2. Experimental

2.1. Materials and mix proportions

Fourteen concrete mixes were prepared according to the mix proportions shown in Table 1. The main mix variables were the free water-to-cement mass ratio (w/c: 0.50 & 0.35) and air content. The cement was a Portland cement CEM 1 42.5 N that complies with EN197-1:2000. Tap water was used as batch water. The aggregates were Thames Valley gravel (5–12.7 mm) and sand (<5 mm) that complies with the BS 882 medium grading. The fine-to-total aggregate mass ratio was 0.40. The 24-hr water absorption of the combined aggregate was 1.5%. Because the aggregate was pre-dried, the amount of water needed to bring it to saturated surface-dry condition was determined and added to the batch water.

A proprietary lignosulphonate based air-entraining agent (AEA) was used to vary the amount of entrained air. The batch water was also corrected for additional water brought in by the air-entraining agent. Several trial mixes were carried out to estimate the AEA dosage to achieve low (L), medium (M) and high (H) air contents, defined arbitrarily as 3%, 6% and 9%, respectively. The air content was measured on freshly mixed concrete using the ASTM C 231 pressure method. Ideally, other mix parameters should be kept constant while the air content is varied, but this is not strictly possible. To increase air content at constant w/c, either the aggregate content or the cement content has to be decreased. Most mixes were designed to have a constant aggregate volume fraction of 67%. Several mixes were designed with less aggregate so that these had the same aggregate-to-cement mass ratio (a/c) or cement content as the control. These mixes are designated with * and + respectively.

2.2. Sample preparation, curing and conditioning

Four cylindrical samples with dimensions 100Ø × 250 mm were prepared for each mix. Materials were batched by mass and mixed with a pan mixer. The samples were compacted in three layers using a vibrating table with adjustable intensity and duration. Each layer was compacted until no significant amount of air bubbles escaped the top surface. The compacted cylinders were then covered with plastic sheets and wet hessian until an age of 24 hours, when they were demoulded. Several curing and conditioning regimes were applied in order to produce samples with a range of maturity, pore characteristics and degree of saturation. Two of the four cylinders from each mix were sealed in cling film and polythene bags, and left to cure at 20 °C for 7 days. The remaining cylinders were cured in a fog room at 95-99% r.h. for 365 days.

After the designated curing period, cylinders were sectioned from the centre to produce three 50 mm thick discs for transport testing and three 8 mm thick discs for point count analysis and electron microscopy. Tests were carried out on the bulk material through a cut face to eliminate possible gradient effects in the cast surface. The end discs, approximately 20 mm thick, were discarded. Sectioning was carried out using a diamond abrasive cutter designed for brittle composite materials operated at a slow feed rate of 0.3 mm/s. Tap water was used as cooling agent. The discs were subsequently towelled dry and conditioned at 20 °C in incubators containing soda lime to absorb CO2, and a motorised fan to generate air circulation. The 7-day old discs were conditioned at 52% r.h, while the 1-year old discs were conditioned at 75% r.h. Saturated salt solutions of $Na_2Cr_2O_7$

Table 1
Mix proportions.

Mix	Water (kg/m^3)	Cement (kg/m^3)	Free w/c	Paste (% vol)	Total aggregate kg/m^3 (% vol)	a/c	AEA (wt. % cement)	Air content (% vol)
C 0.5	194	388	0.5	33	1721 (67)	4.44	0	–
C 0.5 L	183	367	0.5	30	1721 (67)	4.69	0.2	3
C 0.5 M	165	330	0.5	27	1721 (67)	5.21	0.4	6
C 0.5 H	147	294	0.5	24	1721 (67)	5.86	1.0	9
C 0.5 H*	179	357	0.5	29.2	1588 (61.8)	4.44	1.0	9
C 0.5 H+	194	388	0.5	31.7	1523 (59.3)	3.93	1.0	9
C 0.35	161	460	0.35	33	1721 (67)	3.74	0	–
C 0.35 L	157	449	0.35	30	1721 (67)	3.83	0.2	3
C 0.35 L+	161	460	0.35	30.7	1703 (66.3)	3.70	0.2	3
C 0.35 M	142	405	0.35	27	1721 (67)	4.26	0.4	6
C 0.35 M+	161	460	0.35	30.7	1626 (63.3)	3.54	0.4	6
C 0.35 H	126	360	0.35	24	1721 (67)	4.79	0.8	9
C 0.35 H*	150	428	0.35	28.6	1603 (62.4)	3.74	0.8	9
C 0.35 H+	161	460	0.35	30.7	1549 (60.3)	3.37	0.8	9