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Review

Transport properties in unsaturated cement-based materials – A review

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HIGHLIGHTS

- Studies on transport properties in unsaturated cement-based materials are reviewed.
- Experimental methods for measuring transport properties are described.
- Models and modelling for estimating transport properties are addressed.
- Effects of w/c or w/b ratio, chloride binding, SCMs and ITZ are estimated.
- A look to the future, including the research needs to be carried out is presented.

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ABSTRACT

It is certainly true that cement-based materials are rarely saturated in use. Due to their importance to service life prediction and durability assessment of steel reinforced concrete, an increasing attention has been directed to the transport properties in unsaturated cement-based materials over a wide range of water contents in recent years. This review presents recent advances in the understanding of transport properties in unsaturated cement-based materials, including: the experimental approaches, models and modelling for the estimation of ionic diffusivity and gas permeability, the respective influences of water-to-cement (w/c) or water-to-binder (w/b) ratio, chloride binding, supplementary cementitious materials (e.g., silica fume, slag and fly ash), wetting–drying cycles and aggregate-matrix interfacial transition zone (ITZ) on the chloride diffusivity and gas permeability under non-saturated condition. It concludes with a look to the future, including the research needs to be carried out.

Contents

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1. Introduction

The durability problem of cement-based materials has arisen as a result of the premature failure and serviceability issues of many reinforced concrete structures. Concrete durability is to a large extent dependent on their resistance to the ingress of aggressive species, such as chloride, sulphates and carbon dioxide, which result in serious degradation and rebar corrosion of concrete structures. The transport processes of such species through cement-based materials that have complex microstructures are rather complicated and governed by various physical–chemical mechanisms, e.g., diffusion, permeation, absorption and electrical migration. Taking chloride diffusion as an example, chloride ions can penetrate into cement-based materials under a concentration gradient along the connected pore network. During this process some of the chlorides can be captured and immobilized physically/chemically by the hydration products, e.g. calcium silicate hydrate (C–S–H) and calcium monosulfoaluminate hydrate (AFm). This process of interaction between chlorides and cement hydrates is known as chloride binding, which would induce the change of pore structure of cement-based materials and accordingly affect the diffusion of chloride ions. To precisely estimate the chloride diffusivity in cement-based materials, both the complex microstructure and chloride binding should be taken into account.

In general, the corrosion cell requires an unsaturated state, whereby the oxygen can get access to the surface of the reinforcement. In this respect, chloride-induced rebar corrosion occurs only in unsaturated concrete. However, little attention was paid to the transport properties in unsaturated concrete in the past. In addition, the current standard tests rely on concrete being saturated and the service life prediction of reinforced concrete is nowadays designated on saturated model, as most often it is assumed that a properly cured concrete or underwater concrete is completely saturated. Nevertheless, various experimental studies and analysis provide evidences that concrete will remain unsaturated during construction and throughout its long lifetimes [1,2]. In saturated conditions, water is absorbed by the solids inside the porous concrete through the large capillary force. Ions can diffuse through the connected water-filled channels. As the water content decreases, the thickness of absorbed water layers in the porous network and the channels for mass transport are decreased subsequently. In particular at the low saturation level, only very thin water layer absorbed on the pore wall, as a result of which the species penetration becomes much more hardly [3,4].

Water saturation is a key parameter associated with the transport properties. Recently, the central place of transport phenomena in unsaturated condition has been more widely recognized. By fitting the limited experimental results, Saetta et al. [5] was firstly proposed the *S*-shaped curve relation of diffusivity at a given relative humidity (RH). Buchwald [6] quantitatively described the dependence of relative diffusivity on degree of water saturation (SD) in porous building materials. Climent et al. [7] proposed an innovative test method for measuring chloride diffusion through non-saturated concrete by interaction with PVC combustion gases, which contains gas of HCl. The diffusion coefficients were estimated when the atmosphere RH were 54%, 75%, 86% and 95% respectively. Nielsen and Geiker [8] investigated the chloride diffusivity in partially saturated mortar, the results of which were found to agree with the *S*-shaped model proposed by Saetta et al. [5], while at the low RH condition, *S*-shaped curve underestimated the chloride diffusivity. Recently, Olsson et al. [9] evaluated the ion diffusion in non-saturated concrete by resistivity measurements. Dridi and Lacour [10] developed a modified “half-cell” method and analysed the lithium diffusion profile by elemental mapping using the laser-induced breakdown spectroscopy (LIBS) technique in partially saturated cement paste.

Due to the environmental and economic benefit, nowadays supplementary cementitious materials (SCMs), such as silica fume (SF), ground granulated blast-furnace slag (GGBFS), fly ash (FA), limestone powder (LP) and so on have been widely incorporated into binary, ternary and quaternary cement concrete mixes. The addition of SCMs, either reactive or inert, would inevitably change the formation of pore structure because of the changes of initial particle packing and relevant changes of hydration process. Subsequently, the moisture distribution as well as transport properties in unsaturated state would be much different from concrete made of pure ordinary Portland cement (OPC).

Transport properties such as chloride diffusivity and gas permeability are usually considered as indicators to evaluate the durability and predict the service life of reinforced concrete structures. Because of its scientific interest and practical importance, transport properties in unsaturated cement-based materials have been increasingly investigated using both experimental and computational methods. To move forward in this research field for service life prediction and durability assessment, a need arose to review the previous studies regarding the effect of degree of water saturation on transport properties. This review presents recent advances in the knowledge-based relevant to the transport properties in cement-based materials with and without blends in unsaturated condition. Due to space limitations, in this critical review we focus on: the experimental approaches measuring the ionic diffusivity and gas permeability in unsaturated cement-based materials, models and modelling for them, influencing parameters such as water-to-cement (w/c) or water-to-binder (w/b) ratio, SCMs, drying–wetting cycles and aggregate-matrix interfacial transition zone (ITZ).