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Original Research Article

Experimental and numerical investigation of the alkali-silica reaction in the cement-based materials

Witold Grymin [a,*], Dariusz Gawin [a], Marcin Koniorczyk [a], Francesco Pesavento [b]

[a] Department of Building Physics and Building Materials, Lodz University of Technology, Al. Politechniki 6, Łódź 90-92, Poland

[b] Department of Civil, Environmental and Architectural Engineering, University of Padova, Via Marzolo 9, Padova 35131, Italy

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ABSTRACT

The main subject of this paper is the investigation of the influence of the alkali-silica reaction on the microstructure and the transport properties of the cement-based materials. In the experimental research, mortar bars prepared with two different aggregates and stored in conditions of various alkali content were examined. Influence of the reaction on the microstructure of the material was investigated using mercury intrusion porosimetry, water capillary suction test and water vapour adsorption test. Mathematical model of the alkali diffusion and the reaction development is presented. It allows to take into consideration the influence of alkali concentration and aggregate sizes on the reaction development. The numerical code was developed using the finite element, finite difference and Newton-Raphson methods. Good accordance of the results obtained using the proposed model with the experimental data available in literature was obtained.

1. Introduction

Even though dependence between the ASR development and the material microstructure evolution is of paramount significance for predicting durability of the cementitious materials, relatively little research has been devoted to this aspect of the ASR. Yurtdas et al. [1] investigated evolution of porosity and permeability of mortars prepared with reactive, in terms of the ASR, and non-reactive aggregates. Slightly higher values of these parameters were reported for the reactive samples. Lindgård et al. [2] measured, *i.e.*, porosity of concrete samples. For the samples prepared without fly ash and damaged by the ASR, they noticed increase of suction porosity and only negligible changes of macro-porosity. Multiple chemo-mechanical models of the ASR have been formulated. Multon et al. [3] analysed diffusion in aggregates and damage caused by the ASR. Threshold alkali content, below which the reaction does not occur, was introduced. The model was further developed in [4], where effects of the specimen size, the aggregate size and the reactive silica content on the strains were considered. Another approach has

* *Corresponding author.*
E-mail addresses: witold.grymin@p.lodz.pl (W. Grymin), dariusz.gawin@p.lodz.pl (D. Gawin), marcin.koniorczyk@p.lodz.pl (M. Koniorczyk), francesco.pesavento@unipd.it (F. Pesavento).

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Nomenclature

A_c, A_L, B_c, B_L, A_Γ material parameters [–]
$A_{alk,gel}$ alkali content in the gel [–]
c_{alk} concentration of alkalis [–]
$c_{alk,\infty}$ alkali concentration in the undisturbed surrounding [–]
C_p^π specific heat of a phase or its component (π = *alk*, *g*, *l*, *s*, *w* – alkalis, gas, liquid, skeleton, water) [J/(kg K)]
D_D^π effective diffusivity tensor of a phase component (π = *ga*, *gw* – dry air, water vapour) [m^2/s]
D_{alkali} alkali diffusion coefficient [m^2/s]
$D_{alkali,0}$ alkali diffusion coefficient for a fully saturated, unreacted material at a reference temperature [m^2/s]
$D_{alkali,water}$ alkali diffusion coefficient in bulk water [m^2/s]
E_c activation energy of the characteristic time [J/(mol)]
E_L activation energy of the latency time [J/(mol)]
$\mathbf{g}$ gravity acceleration vector [m/s^2]
ΔH_{ASR} enthalpy of the ASR per unit mass [J/kg]
ΔH_{vap} enthalpy of vaporization per unit mass [J/kg]
J_D^π diffusive flux of a phase component in gas phase or liquid phase (π = *alk*, *ga*, *gw* – alkalis, dry air, water vapour) [kg/(m^2 s)]
$\mathbf{k}$ intrinsic permeability tensor [m^2]
$k^{r\pi}$ relative permeability of a phase (π = *g*, *l* – gas, liquid) [–]
$\dot{m}_{alk,gel}$ rate of mass due to binding of alkalis by the ASR gel [kg/(m^3 s)]
$m_{gel,\infty}$ mass of the ASR gel for fully reacted material [kg/(m^3 s)]
$\dot{m}_{gel}$ rate of the gel mass formed during the ASR [kg/(m^3 s)]
$\dot{m}_p$ rate of mass due to evaporation [kg/(m^3 s)]
M^{ASR} water combination coefficient [kg/m^3]
M_π molar mass of a phase or its component (π = *ga*, *g*, *w* – dry air, gas, water) [kg/mol]
n porosity (pore volume/total volume) [–]
$\mathbf{n}$ unit normal vector [–]
p^c capillary pressure [Pa]
p^g gas pressure [Pa]
p^{ga} dry air pressure [Pa]
p^{gw} water vapour pressure [Pa]
q_{alk}, q_{ga}, q_{gw}, q_w imposed fluxes of alkalis, dry air, vapour and liquid water [kg/(m^2 s)]
$\mathbf{q?}$ total heat flux in the domain [W/m^2]
$\mathbf{q?}^\pi$ heat flux in a phase (π = *g*, *l*, *s* – gas, liquid, skeleton) [W/m^2]
R universal gas constant [J/(mol K)]
S_π pore saturation with a phase (π = *g*, *l* – gas, liquid) [–]
t time [s]
t_r characteristic time of the reaction [s]
T absolute temperature [K]
T_{ref} reference temperature for alkali diffusion coefficient [K]
$T_{0,\Gamma}$ reference temperature [K]
T^∞ temperature in undisturbed surrounding [K]
$\mathbf{t}^{tot}$ total stress tensor [Pa]
$\mathbf{t}^\pi$ macroscopic partial stress tensor for a phase (π = *g*, *l*, *s*) [Pa]
$\mathbf{t}^{ef}$ effective stress tensor [Pa]
t imposed traction [Pa]
$\mathbf{u}$ displacement vector [m]
$\mathbf{u}^\pi$ diffusive velocity component of a phase component (π = *alk*, *ga*, *gw* – alkalis, dry air, water vapour) [m/s]
$\mathbf{v}^{\pi s}$ relative velocity of a phase with respect to the skeleton (π = *g*, *l* – gas, liquid) [m/s]
$\mathbf{v}^\pi$ advective velocity of a phase or its component (π = *alk*, *s* – alkalis, skeleton) [m/s]

Greek symbols

α Biot's constant [–]
α_c enthalpy exchange coefficient [m/s]
α_T temperature exponent factor [–]
β_c water vapour exchange coefficient [m/s]
β_s cubic thermal expansion coefficient of the solid [1/K]
β_{sw} total cubic thermal expansion coefficient [1/K]
β_w cubic thermal expansion coefficient of water [1/K]
δ_{ASR} material parameter determining influence of the ASR on the area fraction in contact with liquid phase [–]
δ_c alkali exchange coefficient [m/s]
Γ_{ASR} alkali-silica reaction extent [–]
δ constrictivity [–]
ϵ expansion [–]
ϵ_{ASR} ASR expansion [–]
λ saturation exponent [–]
μ^π dynamic viscosity of a phase (π = *g*, *l* – gas, liquid) [Pa s]
η^π volume fraction of a given phase or its component (π = *alk*, *g*, *ga*, *gw*, *l*, *s*, *w* – alkalis, gas, dry air, water vapour, liquid, skeleton, water) [–]
ρ averaged apparent density of the medium [kg/m^3]
ρ^π intrinsic phase averaged density of a phase or its component (π = *alk*, *g*, *ga*, *gw*, *l*, *s*, *w* – alkalis, gas, dry air, water vapour, liquid, skeleton, water) [kg/m^3]
ρ_π phase averaged density of a phase or its component (π = *alk*, *g*, *ga*, *gw*, *l*, *s*, *w* – alkalis, gas, dry air, water vapour, liquid, skeleton, water) [kg/m^3]
ρ_∞^{gw} water vapour density in undisturbed surrounding [kg/m^3]
τ tortuosity factor [–]
τ_{aging} characteristic time of the gel aging process [s]
τ_c characteristic time of the ASR swelling [s]
τ_{c0} characteristic time of the ASR swelling for a fully saturated material and for the reference temperature [s]
τ_L latency time of the ASR swelling [s]
τ_{L0} latency time of the ASR swelling for a fully saturated material and for the reference temperature [s]
χ_{ef} effective thermal conductivity [W/(m K)]