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Surface fractal dimension: An indicator to characterize the microstructure of cement-based porous materials

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ABSTRACT

This study investigates the surface fractal dimensions (SFDs) of pore structure of cement pastes and mortars with/without ground granulated blast-furnace slag (GGBS) incorporated into binder. The samples were subject to water curing and sealed curing. The fractal dimensions of samples are determined by Zhang's model (Ind Eng Chem Res, 34 (1995):1383–1386) on the basis of mercury intrusion porosimetry (MIP) data. The results confirm the scale-dependent property of fractal dimension of pore structures and the micro-fractal, transition and macro-fractal regions are identified for all samples. The upper pore size range for micro-fractal regions is around 30 nm, the transition regions cover 0.5–2 magnitude orders of pore size and macro fractal regions cover 1.5–3 magnitude orders. Both curing conditions and GGBS in binder have impact on the fractal properties of pore structure, and samples incorporating GGBS have substantially larger values for micro-fractal regions.

1. Introduction

The mechanical and durability properties of cement-based porous materials are intimately related to their pore structure. Despite the available experimental techniques, the characterization of pore structure remains a complex issue for cement-based materials since the involved scales for pore size range from nanometer (e.g. C-S-H assemblage and inter-granular pores) to millimeter (e.g. entrapped air voids) [1]. The most used parameters of pore structure characterization include porosity, pore size distribution and specific surface area. These parameters are global features of pore structure and provide no information on the packing patterns of solids phases. The fractal dimension, defined in fractal geometry [2], has been applied to characterize the texture of porous materials [3–5]. The fractal properties of internal surface of porous materials can be evaluated from nitrogen adsorption/desorption (NAD) [6,7], small-angle scattering of X-rays (SAXS) or neutrons (SANS) [8,9], nuclear magnetic resonance (NMR) [10], scanning electronic microscopy (SEM) [11], and mercury intrusion porosimetry (MIP) [12–14]. The pore size ranges from these methods are different: SAX(N)S, NAD and NMR cover the range between 1 nm and 100 nm, SEM images can capture pore geometry in range of > 10 μm, MIP can cover a relatively large range of 1 nm–1 mm. Through appropriate interpretation (e.g. [13,15]), the surface fractal dimension (SFD) has been used to characterize the microstructure of soils, rocks, porous ceramic gels and cement pastes [12–14,16,17]. Moreover, it was found that the fractal dimensions of pore structure can be related to the transport properties of porous materials [18]. Although some investigations have been undertaken on cement pastes [8,9,14,19], more research is deserved to understand the fractal properties of cement-based materials in terms of the packing patterns of solid phases as well as the hydration aspects of cementitious binders. This paper evaluates the SFD of cement-based materials on the basis of MIP data, and intends to explore the relationship between the packing patterns of solid phases of hydrates and the fractal properties of material pore structure.

2. Experimental and results

The cement-based materials for fractal dimension analysis are presented in Table 1 with "OPC" standing for ordinary Portland cement, "GGBS" for ground granulated blast-furnace slag, and "w/b ratio" for the mass ratio between water and binder in material mix proportioning. The volumetric ratio of fine aggregates in mortar specimens is kept as 0.43. The specimens were water-cured or sealed-cured to the age of 90d. Then samples were taken from the specimens and subject to MIP measurement with the intrusion pressure ranging from 1.4 kPa to 414 MPa. The fractal model retained for fractal analysis of pore structure is due to Zhang et al. [12,13]. This model evaluates the fractal dimension of internal

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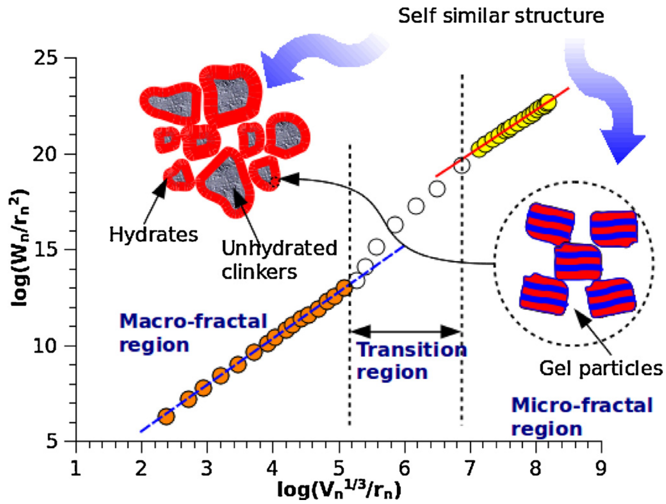

Fig. 1. Scale-dependent surface fractal dimensions evaluated by Zhang's model for cement-based porous materials (PNS-30 data)

surface of pore structure through the equilibrium between the surface energy increase of nonwetting surface extension and the necessary external work for mercury penetrating. The intruded work W_n, intruded mercury volume V_n and fractal dimension D_s obey,

$$ln\left(\frac{W_n}{r_n^2}\right) = D_s \ln\left(\frac{V_n^{1/3}}{r_n}\right) + C \quad (1)$$

The intrusion work $W_n = \sum_{i=1}^{n} P_i \Delta V_i$ with P_i and V_i as the applied pressure and intruded pore volume at step i, r_n stands for the smallest pore radius, and C a constant. From the MIP results, the intrusion work W_n is calculated and the fractal dimension is evaluated through Eq. (1) as the slope of the curve $\ln(W_n/r_n^2)$ versus $\ln(V_n^{1/3}/r_n)$. Fig. 1 illustrates the fractal analysis results for PNS-30 specimen. A scale-dependent property is observed for the surface fractal dimension, and this property has been observed for other cement pastes [14] and porous materials [13]. The pore structure shows two fractal regions with well defined D_s, separated by a transition region without clear fractal property. According to Zeng et al. [14], the two fractal regions correspond respectively

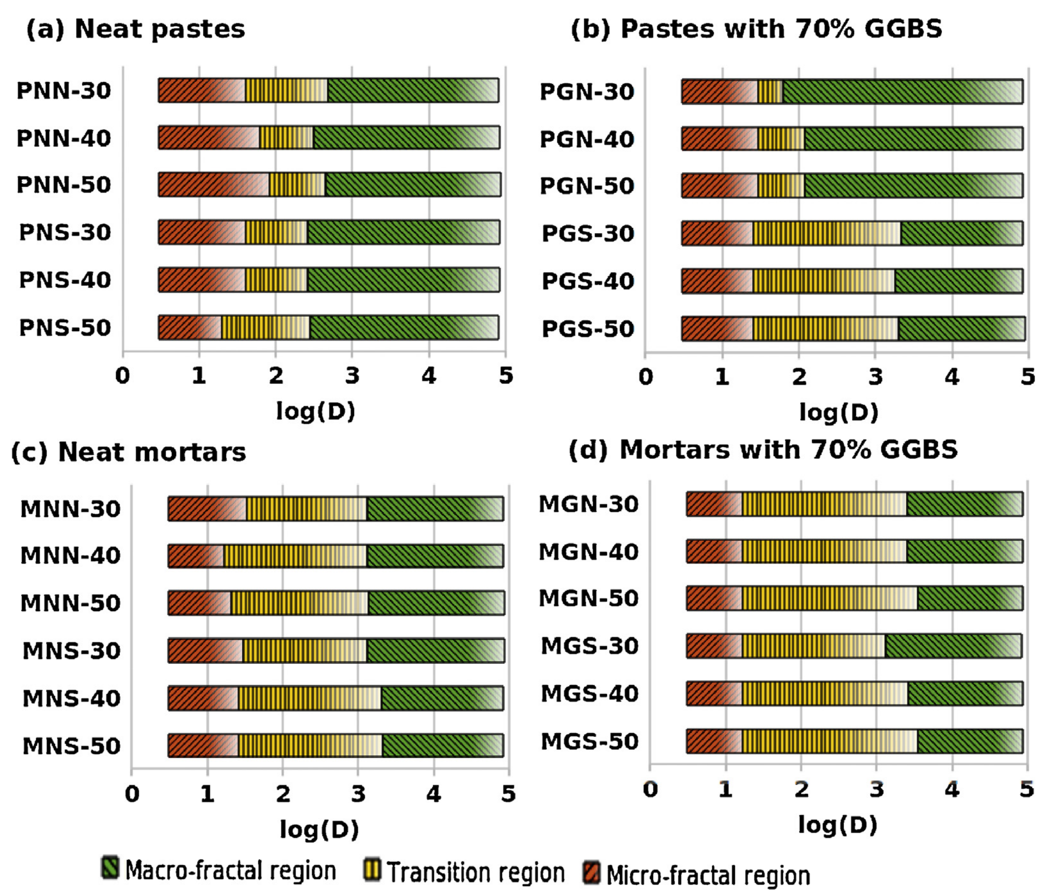

Fig. 2. Pore size ranges for different fractal regions for (a) neat pastes, (b) pastes blended with 70% GGBS, (c) neat mortars and (d) mortars blended with 70% GGBS