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Editorial for Special Issue "Fractal and Fractional in Cement-Based Materials"

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Cement-based materials, including cement paste, mortar, and concrete, are the most widely used construction materials in the world. Cement-based materials have played a vital role in the development of the national economy and in the construction of infrastructure. The microstructural investigation of cement-based materials has always received widespread attention from global scientists and engineers. There is a common consensus that the properties of cement-based materials at the macro-level are closely related to their material structure at the micro- and meso-scales. A better understanding of the structure–property relationships is essential to the novel design and usage of these materials in practice.

In recent years, fractal theory has provided a new perspective with which to probe the structure–property relationships of cement-based materials. Fractal theory is a new branch of mathematics, proposed and fundamentally established by French mathematician, Mandelbrot, in 1977, focusing on the irregularities, as well as the haphazard phenomena and behaviors, in nature. Since then, fractal theory has been rapidly applied in many research fields, such as civil engineering, materials science, information science, and computer science. The fractal dimension is one of the core contents of fractal theory and can be used to characterize the complexity and irregularity of the microstructures and mesostructures of cement-based materials. The fractal dimensions have been proven again and again to be closely related to the macro-performance of cement-based materials, such as mechanical properties, volumetric stability, permeability, and durability.

This Special Issue gathers 12 papers on the study and application of fractal and fractional theories in the research field of cement-based materials. These papers include the following: (1) a fractal characterization of construction materials from a multiscale viewpoint; (2) fractals combined with other theoretical, numerical and/or experimental methods in the evaluation of the mechanical performance/durability of cement-based materials; (3) fractal approaches to studying the evolution of pore structure of hydrating cement-based materials; (4) fractal approaches to studying the evolution of solid phases of hydrating cement-based materials; (5) other fractal-based approaches in construction materials. An overview of these papers is given as follows.

In a review conducted by Wang et al. [1], the application of fractal theory in the research field of cement-based materials was comprehensively reviewed. This review work includes three aspects: (1) a detailed summary of the principles and classification of the seven commonly used fractal dimensions applied in the research field of cement-based materials, including the fractal dimensions of the pore surface (D_s), pore volume (D_v), pore tortuosity (D_t), air void (D_a), fracture surface (D_{fs}), cracks (D_c) and the particle size distribution or particle spatial distribution (D_p); (2) a summary and analysis of the testing techniques and fractal models determining and calculating these fractal dimensions; (3) an introduction to and discussion of the application of fractal theory for studying the macro-properties of cement-based materials, including the mechanical properties, volumetric stability, durability, fracture mechanisms and fracture mechanics, flexural performance and fracture energy, and pozzolanic reactivity of the mineral materials, as well as the dispersion state of the powders. This review paper also concluded that, although lots of meaningful and significant results have been obtained in this filed, there are also some drawbacks and aspects that need to be further considered and carried out.

The main hydration product of cement-based materials is calcium silicate hydrate (C–S–H) gel, which is considered to be the main binding phase in cement-based materials. In another review work by Tang et al. [2] in this Special Issue, different C–S–H gel preparation methods were compared, the structure of C–S–H gels and the structure of C–S–H globules were discussed in terms of different models and molecular dynamics simulations, and the fractal characteristics and fractal dimensions of C–S–H gel were summarized. In addition, the mechanical properties and durability of C–S–H, including its resistance to carbonization and chloride/sulfate attacks, were reviewed and summarized.

At present, low-heat Portland (LHP) cement is widely used in mass concrete structures to reduce the cracking risk. Wang et al. [3] compared the influence of two types of MgO on the hydration as well as the shrinkage behavior of LHP cement-based materials via pore structural and fractal analysis. The main results indicate the following: (1) The addition of reactive MgO (with a reactivity of 50 s and shortened as M50 thereafter) not only extends the induction stage of LHP cement by about 1–2 h, but also slightly increases the hydration heat. In contrast, the addition of weak reactive MgO (with a reactivity of 300 s and shortened to M300 thereafter) could not prolong the induction stage of LHP cement. (2) M50 effectively compensates the shrinkage of LHP concrete at a much earlier time than M300, whereas M300 compensates the long-term shrinkage more effectively than M50. (3) The fractal dimension is closely correlated with the pore structure of LHP concrete. Both pore structure and fractal dimension exhibit weak (or no) correlations with a shrinkage of LHP concrete.

In An et al.'s study [4], a novel approach fusing the fractal dimension and the UHK-Net deep learning network was proposed to recognize concrete cracks and to determine the location of concrete cracks. The U-Net Haar-like (UHK-Net) network was adopted to construct the crack segmentation network. The advantages of their proposed method were compared with the FCN, U-Net, and YOLO v5 networks. The results show that the pixel accuracy, mean pixel accuracy, and mean intersection over the union of crack segmentation, as determined by their proposed method, were all greater than 90%. The proposed method not only characterizes the dark-crack images, but also distinguishes small- and fine-crack images.

Fiber is effective in restricting concrete cracks and improving the toughness of cement-based material. In the study conducted by Li et al. [5], flexural tests of polypropylene fiber-reinforced geopolymer mortar were conducted, the surface cracking images were collected by a digital camera, and the cracking information was extracted using deep learning. Their results showed that: (1) the mean intersection over union and mean pixel accuracy of the cracks were 0.8451 and 0.9213, respectively; (2) the crack length, width, area and fractal dimension of the specimen increased with the increase in the fiber volume fraction; (3) the variation in the bottom crack length and the side crack fractal dimension can be used to represent the overall crack variation patterns.

Alkalis mainly exist in the form of different alkali sulfates in cement-based materials. Li et al.'s [6] study, in this Issue, investigated the impacts of different alkali sulfates on the shrinkage, hydration, pore structure, fractal dimension and microstructure of low-heat Portland cement (LHPC), medium-heat Portland cement (MHPC) and ordinary Portland cement (OPC). Their results indicate that alkali sulfates magnify the autogenous shrinkage and drying shrinkage of cement-based materials. Compared with the pore size distribution, the fractal dimension can better characterize the shrinkage properties of cement-based materials. It is noted that the contribution of K_2SO_4 (K alkali) to the promotion effect of shrinkage on cement-based materials is more significant than that of Na_2SO_4 (Na alkali). The microstructure investigation of different cement-based materials by means of nuclear magnetic resonance (NMR), mercury intrusion porosimetry (MIP) and scanning electron microscope (SEM) shows that this effect may be related to the differences in the pore structures, crystal forms and morphologies of hydration products.

Concrete durability is closely related to the safety and service life of concrete structures. Want et al. [7] conduced a pore structural and fractal analysis of the effects of MgO reactivity and dosage on the permeability and F–T resistance of concrete. The following conclusions can be obtained from this work: (1) The permeability of concrete is closely related to the pore structure. M50 can densify the pore structure and lower the fraction of large capillary pores at an early age; thus, it is beneficial for the impermeability of concrete. By contrast, M300 can enhance the 180-day impermeability of concrete, since it can densify the pore structure only at a late age. (2) The influence of MgO on F–T resistance is minor, since MgO could not change the air void parameters. (3) The fractal dimension of a pore surface (D_s) exhibits a close relationship with the permeability property of concrete. However, no correlation can be found between the F–T resistance of concrete and D_s.

When exposed to sulfuric acid environments, the service life of concrete structures is reduced due to the high alkalinity of concrete. Xiao et al. [8] investigated the influence of the water/cement ratio, the pH value of the solution, and the chemical composition of the aggregate on the resistance of concrete subjected to sulfuric acid. Their results showed that the larger the water/cement ratio, the smaller the mass loss and the surface fractal dimension of the specimens; with the decrease in the pH value of the sulfuric acid solution, the mass loss and the surface fractal dimension of the specimens was increased.

In Xiao et al.'s other work [9] in this Issue, the effect of fine marble aggregate on the shear strength and fractal dimension of the interface between soil and concrete corroded by sulfuric acid was studied. A 3D laser scanner was employed to obtain the digital shapes of concrete plates subjected to sulfuric acid, and the rough surfaces were evaluated using fractal dimension analysis. Large direct shear experiments were also performed to obtain the curves of the interface shear stress and the shear displacement between sand and the corroded concrete plate. The data fitting method was adopted to calculate the parameters of shear strength (i.e., friction angle and cohesive) and the parameters of the Clough–Duncan hyperbolic model. The results indicated that as the corrosion time increased, the surface of the concrete plate became rougher, the surface fractal dimensions of the concrete corroded by sulfuric acid became bigger, and the interface friction angle became greater.

Magnesium oxysulfate (MOS) cement is a typical eco-friendly cementitious material, which offers excellent performances. In Huang et al.'s [10] study, a novel multiscale modeling strategy was proposed to simulate the hydration and pore structure of the MOS cement system. The results showed that a large M ($MgO/MgSO_4$) was beneficial for the formation of $5Mg(OH)_2 \cdot MgSO_4 \cdot 7H_2O$ and a large H ($H_2O/MgSO_4$) tended to decompose MOS cement paste and cause leaching. The visual results of the matrix laboratory (in MATLAB) showed that a large M and small H were helful in reducing porosity. The fractal dimension of the pore structure (D_f) was significantly decreased after the hydration of MOS. D_f was found to be positively correlated to the porosity of the paste, while the large M and small H values were beneficial for modifying the microstructure of MOS paste by decreasing the value of D_f.

Highly piezoresistive cement-based materials (CBMs) are urgently needed for the development of self-sensing smart structures and buildings. In Dang et al.'s [11] work in this Issue, the piezoresistivity of cement mortar with different dosages of graphene nanoplatelets (GNPs) was investigated, while the microstructure was assessed using electron scanning microscopy (SEM) and mercury intrusion porosimetry (MIP). The results show that the incorporation of GNPs into cement mortar can roughen the fracture surfaces due to the agglomeration of GNPs. The fractal dimensions in macro- and micro-fractal regions vary with the GNP content. GNPs not only affect the fractal structure of cement mortar, but also alter the tunneling and contact effects that govern the piezoresistivity of composite materials.

Ullah et al.'s [12] study in this Issue shows how to utilize fractal geometry to model porous structures and then print them using 3D-printing technology. A mathematical procedure was developed to create stochastic point clouds using the affine maps of a predefined iterative function systems (IFS)-based fractal. In addition, a method was developed to modify a given IFS fractal-generated point cloud. The model can be transformed into a 3D computer-aided design (CAD) model. The efficacy of the proposed method is demonstrated by transforming the Sierpinski carpet (an IFS-based fractal) into a 3D-printed porous structures. The results of this study can be used to optimize the experimental studies on printing real porous structures.

It is expected that the collected papers may help to inspire new ideas and provide a basic guide for researchers who want to study cement-based materials in terms of fractal theory. The aim of this Special Issue is also to promote a deeper and more comprehensive investigation and application of the fractal and the fractional in cement-based material research.

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References

1. Wang, L.; Zeng, X.; Yang, H.; Lv, X. Investigation and application of fractal theory in cement-based materials: A review. *Fractal Fract.* **2021**, *5*, 247. [CrossRef]
2. Tang, S.W.; Wang, Y.; Geng, Z.C.; Xu, X.F.; Yu, W.Z. Structure, fractality, mechanics and durability of calcium silicate hydrates. *Fractal Fract.* **2021**, *5*, 47. [CrossRef]
3. Wang, L.; Lu, X.; Liu, L.; Xiao, J.; Zhang, G.; Guo, F.; Li, L. Influence of MgO on the hydration and shrinkage behavior of low heat Portland cement-based materials via pore structural and fractal analysis. *Fractal Fract.* **2022**, *6*, 40. [CrossRef]
4. An, Q.; Chen, X.; Wang, H.; Yang, H.; Yang, Y. Segmentation of concrete cracks by using fractal dimension and UHK-net. *Fractal Fract.* **2022**, *6*, 95. [CrossRef]
5. Li, L.; Sun, H.; Zhang, Y.; Yu, B. Surface cracking and fractal characteristics of bending fractured polypropylene fiber-reinforced geopolymer mortar. *Fractal Fract.* **2021**, *5*, 142. [CrossRef]
6. Li, Y.; Zhang, H.; Huang, M.; Yin, H.; Jiang, K.; Xiao, K.; Tang, S. Influence of different alkali sulfates on the shrinkage, hydration, pore structure, fractal dimension and microstructure of low-heat Portland cement, medium-heat Portland cement and ordinary Portland cement. *Fractal Fract.* **2021**, *5*, 79. [CrossRef]
7. Wang, L.; Song, X.; Yang, H.; Wang, L.; Tang, S.; Wu, B.; Mao, W. Pore structural and fractal analysis of the effects of MgO reactivity and dosage on permeability and F–T resistance of concrete. *Fractal Fract.* **2022**, *6*, 113. [CrossRef]
8. Xiao, J.; Long, X.; Li, L.; Jiang, H.; Zhang, Y.; Qu, W. Study on the influence of three factors on mass loss and surface fractal dimension of concrete in sulfuric acid environments. *Fractal Fract.* **2021**, *5*, 146. [CrossRef]
9. Xiao, J.; Xu, Z.; Murong, Y.; Lei, B.; Chu, L.; Jiang, H.; Qu, W. Effect of chemical composition of fine aggregate on the frictional behavior of concrete–soil interface under sulfuric acid environment. *Fractal Fract.* **2022**, *6*, 22. [CrossRef]
10. Huang, J.; Li, W.; Huang, D.; Chen, E. Fractal analysis on pore structure and hydration of magnesium oxysulfate cements by first principle, thermodynamic and microstructure-based methods. *Fractal Fract.* **2021**, *5*, 164. [CrossRef]
11. Dang, N.; Tao, J.; Zeng, Q.; Zhao, W. May the piezoresistivity of GNP-modified cement mortar be related to its fractal structure? *Fractal Fract.* **2021**, *5*, 148. [CrossRef]
12. Ullah, A.S.; Addona, D.M.; Seto, Y.; Yonehara, S.; Kubo, A. Utilizing fractals for modeling and 3D printing of porous structures. *Fractal Fract.* **2021**, *5*, 40. [CrossRef]