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Editorial

Sustainable High-Performance Hydraulic Concrete

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1. Introduction

Concrete has always been indispensable as a material for the engineering and construction of hydraulic structures (e.g., dams, underwater tunnels, sluices, and other underwater buildings) [1]. Currently, a series of world-class huge hydropower stations, such as the Yebatan arch dam (located at the boundary between Sichuan and Tibet, 217 m), Wudongde arch dam (in Sichuan, 270 m), Liangjiangkou rockfill dam (in Sichuan, 295 m), Shuangjiangkou rockfill dam (in Sichuan, 315 m), etc., are being built in the southwest of China [2]. The construction of these hydraulic projects, especially the concrete dam, needs a huge amount of hydraulic concrete [3,4].

Hydropower resources are often distributed in alpine regions, which are characterized by complex terrain, large climate changes, and frequent extreme weather. Such harsh environments undoubtedly pose new challenges for the durability of hydraulic concrete, which is easily damaged by various environmental factors [5]. The main damages of hydraulic concrete caused by the harsh environments can be classified into the following forms: (1) freezing and thawing damage of concrete in cold regions where air temperatures as low as −20 °C are common during winter months [6]; (2) abrasion damage of concrete in spillway, the flood discharge tunnel and the overflow surface of the hydropower stations, is often caused by high-speed water flow (40–100 m/s) containing sand and gravel due to high water pressure (200–300 m water heat) [7]; (3) deterioration of concrete due to the erosion of adverse ions such as chloride and sulfate in underground water and ocean regions [8–11]; (4) dissolution due to the flowing soft water action which could lower the concentration of liquid lime in concrete and cause decomposition of hydration products in some cases, resulting in weakened mechanical and durability performance and even structure failure [12]; (5) seepage failure by the high water pressure [13]; (6) plastic and drying shrinkage caused by the evaporation of water in drying environments or strong wind [2]; (7) autogenous shrinkage caused by a low water to binder ratio and the usage of some extreme fine powders such as silica fume [14]; (8) thermal stress due to temperature differences and fluctuations [15], etc. Temperature rising and shrinkage are particularly important to hydraulic mass concrete projects, in which cracking may occur due to the temperature gradient or shrinkage [16]. It is generally recognized that cracks could weaken the performance and durability of concrete and even jeopardize the integrity of hydraulic concrete structures [17]. In fact, concrete often fails before reaching its designed service life due to these environmental damages. However, this is not the only issue facing the

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industry: Recent changes in general green awareness have meant that the development of sustainable hydraulic concrete is now inevitable.

The main features of sustainable hydraulic concrete are a low amount of cement [2,4] and utilization of a large amount of supplementary cementitious materials (SCMs) such as fly ash, slag, limestone powder, and so on [18–20]. Since hydraulic concrete is a typical mass concrete, low cement content and high mineral admixture amount (as high as 70% or even more) are beneficial to reduce the hydration heat caused by cement hydration [15]. However, both features inevitably lower the early concrete strength and consequently slow down the construction process. There are several strategies to develop sustainable hydraulic concrete. For instance, to increase the toughness of concrete, many kinds of fibers are widely used to develop sustainable hydraulic concrete with high ductility [21,22]; in recent years, to reduce the thermal shrinkage and reduce the cracking risk, low heat Portland cement has been used to lower the cement hydration heat [14,23,24]; to improve the mechanical properties and microstructure of concrete, nanomaterials such as silica fume are adopted [14,25]; to compensate the drying shrinkage and autogenous shrinkage, MgO expansion agent is used, etc. [26,27]. Overall, many innovations in sustainable hydraulic concrete have enabled the design and construction of sustainable and durable infrastructure.

Moreover, hydraulic concrete shows highly heterogeneous compositions and complex spatial distributions, from the nano- to the macroscales [28,29]. It is widely accepted that the macro-level properties of concrete, e.g., the mechanical properties, volumetric shrinkage, permeability, and durability, are intrinsically related to their material structure at the micro- and mesoscales [30–32]. Therefore, the investigation of microstructures is essential to accurately evaluate the macro-mechanical performances of hydraulic concrete. In addition, the increase in demand for high-performance hydraulic concrete has resulted in renewed interest in the study of the new technologies and new theories for investigating microstructures and enhancing the performance of concrete [13,33–35].

This special issue gathers two papers regarding the investigation of durability, preparation, and microstructure of hydraulic concrete and aims at providing contributions on the topic of sustainable high-performance hydraulic concrete.

2. Overview of This Special Issue

Various kinds of pores and microcracks are distributed in concrete, which could significantly affect the elastic modulus of porous materials. To investigate the effects of porosity and aggregate gradation on the elastic modulus of concrete, Zhang et al. [36] developed a four-phase model, which takes aggregate gradation and porosity into account in the prediction of the elastic modulus of concrete, based on the micromechanical theories. The model has been verified with their experimental results. First, using the Mori Tanaka and differential self-consistent methods, the pores in both the mortar and interfacial transition zone (ITZ) were homogenized. Then, the continuously graded aggregates were divided into finite aggregate size intervals. Further, based on the generalized self-consistent model and multiphase composite model derived from the Mori Tanaka method, an aggregate gradation model for the prediction of the elastic modulus of concrete was developed. By simulating the pores in concrete with expanded polystyrene sphere grains, the effect of overall porosity on the elastic modulus of concrete was investigated. The research results show that aggregate gradation and porosity have a remarkable influence on the elastic modulus of concrete, and the proposed model is effective to estimate the elastic modulus of concrete, the deviation between the predicted elastic modulus and experimental elastic modulus is less than 8%. The elastic modulus decreases with increasing ITZ porosity. However, for ITZ porosity exceeding 40%, the decrease in the elastic modulus is large with increasing ITZ porosity. For a fixed overall porosity, the ITZ porosity owned more influences than the mortar porosity on the elastic modulus of concrete. Enhancing the ITZ elastic modulus and decreasing the ITZ thickness are efficient in increasing the elastic modulus of concrete.

Magnesium oxychloride cement (MOC) foam concrete (MOCFC) is an air-hardening cementing material formed by mixing magnesium chloride solution ($MgCl_2$) and light-burned magnesia (i.e., active MgO) [37,38]. In practical application, adding caustic dolomite powder into light-burned magnesite powder can reduce the MOCFC production cost. The brine content of MOC changes with the incorporation of caustic dolomite powder. The study of Zheng et al. [39] in this special issue investigated the relationship between the mass percent concentration and the Baumé degree of a magnesium chloride solution after bischofite ($MgCl_2 \cdot 6H_2O$) from a salt lake was dissolved in water. Then the proportional relationship between the amount of water in brine and bischofite and the functional formula for the water-to-cement ratio (W/C) of MOC mixed with caustic dolomite powder were deduced. Finally, the functional relationship was verified as feasible for preparing MOC through the experiment.

3. Conclusions

In this special issue, two papers were collected regarding the investigation of durability, preparation, and microstructure of hydraulic concrete. The aforementioned are the state-of-the-art studies, aiming at providing contributions on the topic of sustainable high-performance hydraulic concrete. New technologies and theories for investigating microstructures and enhancing the performance of hydraulic concrete will be gathered in other issues.

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References

1. Wang, X.; Wu, D.; Zhang, J.; Yu, R.; Hou, D.; Shui, Z. Design of sustainable ultra-high performance concrete: A review. *Constr. Build. Mater.* **2021**, *307*, 124643. [CrossRef]
2. Wang, L.; Yang, H.Q.; Zhou, S.H.; Chen, E.; Tang, S.W. Mechanical properties, long-term hydration heat, shinkage behavior and crack resistance of dam concrete designed with low heat Portland (LHP) cement and fly ash. *Constr. Build. Mater.* **2018**, *187*, 1073–1091. [CrossRef]
3. Wang, L.; Guo, F.X.; Lin, Y.Q.; Yang, H.M.; Tang, S.W. Comparison between the effects of phosphorous slag and fly ash on the C-S-H structure, long-term hydration heat and volume deformation of cement-based materials. *Constr. Build. Mater.* **2020**, *250*, 118807. [CrossRef]
4. Lv, X.D.; Shen, W.G.; Dong, Y.; Zhang, J.F.; Xie, Z.Q. A comparative study on the practical utilization of iron tailings as a complete replacement of normal aggregates in dam concrete with different gradation. *J. Clean. Prod.* **2019**, *211*, 704–715. [CrossRef]
5. Dong, Y.; Yang, H.; Rao, M. Effects of mineral admixture on the carbonic acid leaching resistance of cement-based materials. *Ceramics–Silikaty* **2017**, *61*, 276–284. [CrossRef]
6. Wang, L.; Guo, F.X.; Yang, H.M.; Wang, Y.; Tang, S.W. Comparison of fly ash, PVA fiber, MgO and shrinkage-reducing admixture on the frost resistance of face slab concrete via pore structural and fractal analysis. *Fractals* **2021**, *29*, 2140002. [CrossRef]
7. Wang, L.; Jin, M.M.; Guo, F.X.; Wang, Y.; Tang, S.W. Pore structural and fractal analysis of the influence of fly ash and silica fume on the mechanical property and abrasion resistance of concrete. *Fractals* **2021**, *29*, 2140003. [CrossRef]

8. Lv, X.; Dong, Y.; Wang, R. Resistance improvement of cement mortar containing silica fume to external sulfate attacks at normal temperature. *Constr. Build. Mater.* **2020**, *258*, 119630. [CrossRef]
9. Xiao, J.; Long, X.; Qu, W.; Li, L.; Jiang, H.; Zhong, Z. Influence of sulfuric acid corrosion on concrete stress-strain relationship under uniaxial compression. *Measurement* **2021**, *185*, 110318. [CrossRef]
10. Wang, X.; Yu, R.; Shui, Z.; Song, Q.; Zhang, Z. Mix design and characteristics evaluation of an eco-friendly Ultra-High performance concrete incorporating recycled coral based materials. *J. Clean. Prod.* **2017**, *165*, 70–80. [CrossRef]
11. Cheng, X.; Xia, J.; Wu, R.J.; Jin, W.L.; Pan, C.G. Optimisation of sacrificial anode cathodic protection system in chloride-contaminated reinforced concrete structure. *J. Build. Eng.* **2022**, *45*, 103515. [CrossRef]
12. Wang, L.; Jin, M.; Zhou, S.; Tang, S.W.; Lu, X. Investigation of microstructure of C-S-H and micro-mechanics of cement pastes under NH_4NO_3 dissolution by ^{29}Si MAS NMR and microhardness. *Measurement* **2021**, *185*, 110019. [CrossRef]
13. Wang, L.; Luo, R.Y.; Zhang, W.; Jin, M.M.; Tang, S.W. Effects of fineness and content of phosphorus slag on cement hydration, permeability, pore structure and fractal dimension of concrete. *Fractals* **2021**, *29*, 2140004. [CrossRef]
14. Wang, L.; Jin, M.M.; Wu, Y.H.; Zhou, Y.X.; Tang, S.W. Hydration, shrinkage, pore structure and fractal dimension of silica fume modified low heat Portland cement-based materials. *Constr. Build. Mater.* **2021**, *272*, 121952. [CrossRef]
15. Xie, Z.; Zhu, Z.; Fu, Z.; Lv, X. Simulation of the temperature field for massive concrete structures using an interval finite element method. *Eng. Comput.* **2020**, *37*, 45. [CrossRef]
16. Jung, S.H.; Choi, Y.C.; Choi, S. Use of ternary blended concrete to mitigate thermal cracking in massive concrete structures-A field feasibility and monitoring case study. *Constr. Build. Mater.* **2017**, *137*, 208–215. [CrossRef]
17. Yen, T.; Hsu, T.-H.; Liu, Y.-W.; Chen, S.-H. Influence of class F fly ash on the abrasion–erosion resistance of high-strength concrete. *Constr. Build. Mater.* **2007**, *21*, 458–463. [CrossRef]
18. Wang, L.; Yang, H.Q.; Dong, Y.; Chen, E.; Tang, S.W. Environmental evaluation, hydration, pore structure, volume deformation and abrasion resistance of low heat Portland (LHP) cement-based materials. *J. Clean. Prod.* **2018**, *203*, 540–558. [CrossRef]
19. Hu, L.L.; He, Z.; Shao, Y.X.; Cai, X.H.; Zhang, S.P. Microstructure and properties of sustainable cement-based materials using combustion treated rice husk ash. *Constr. Build. Mater.* **2021**, *294*, 123482. [CrossRef]
20. Hu, L.L.; He, Z. A fresh perspective on effect of metakaolin and limestone powder on sulfate resistance of cement-based materials. *Constr. Build. Mater.* **2020**, *262*, 119847. [CrossRef]
21. Wang, L.; He, T.S.; Zhou, Y.X.; Tang, S.W.; Tan, J.J.; Liua, Z.T.; Su, J.W. The influence of fiber type and length on the cracking resistance, durability and pore structure of face slab concrete. *Constr. Build. Mater.* **2021**, *282*, 122706. [CrossRef]
22. Zhang, P.; Wang, K.X.; Wang, J.; Guo, J.J.; Hu, S.W.; Ling, Y.F. Mechanical properties and prediction of fracture parameters of geopolymer/alkali-activated mortar modified with PVA fiber and nano-SiO2. *Ceram. Int.* **2020**, *46*, 20027–20037. [CrossRef]
23. Cai, J.X.; Zhang, C.M.; Zeng, L.; Xu, H.; Wang, J.; Liu, K.Q.; Cheng, X.W. Preparation and action mechanism of temperature control materials for low-temperature cement. *Constr. Build. Mater.* **2021**, *312*, 125364. [CrossRef]
24. Li, Y.; Zhang, H.; Huang, M.H.; Yin, H.B.; Jiang, K.; Xiao, K.T.; Tang, S.W. Influence of different alkali sulfates on the shrinkage, hydration, pore structure, fractal dimension and microstructure of low-heat portland cement, medium-heat Portland cment and ordinary Portland cement. *Fractal Fract.* **2021**, *5*, 79. [CrossRef]
25. He, W.; Hao, W.; Meng, X.; Zhang, P.; Sun, X.; Shen, Y. Influence of graphite powder on the mechanical and acoustic emission characteristics of concrete. *Buildings* **2022**, *12*, 18. [CrossRef]
26. Wang, L.; Li, G.; Li, X.; Guo, F.; Tang, S.; Lu, X.; Hanif, A. Influence of reactivity and dosage of MgO expansive agent on shrinkage and crack resistance of face slab concrete. *Cem. Conc. Compos.* **2022**, *126*, 104333. [CrossRef]
27. Ruan, S.; Unluer, C. Comparison of the environmental impacts of reactive magnesia and calcined dolomite and their performance under different curing conditions. *J. Mater. Civ. Eng.* **2018**, *30*, 04018279. [CrossRef]
28. 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]
29. Shi, Y.; Dong, Y.; Chen, X.; Li, X. Different chemical composition of aggregate impact on hydraulic concrete interfacial transition zone. *Asian J. Chem.* **2014**, *26*, 1267–1270. [CrossRef]
30. 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]
31. Zhang, P.; Gao, Z.; Wang, J.; Wang, K. Numerical modeling of rebar-matrix bond behaviors of nano-SiO2 and PVA fiber reinforced geopolymer composites. *Ceram. Int.* **2021**, *47*, 11727–11737. [CrossRef]
32. Zhang, P.; Gao, Z.; Wang, J.; Guo, J.; Hu, S.; Ling, Y. Properties of fresh and hardened fly ash/slag based geopolymer concrete: A review. *J. Clean. Prod.* **2020**, *270*, 122389. [CrossRef]
33. Xiao, J.; Xu, Z.; Murong, Y.; Wang, L.; 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]
34. 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]
35. 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]
36. Zhang, G.; Yang, Z.; Yan, Y.; Wang, M.; Wu, L.; Lei, H.; Gu, Y. Experimental and theoretical prediction model research on concrete elastic modulus influenced by aggregate gradation and porosity. *Sustainability* **2021**, *13*, 1811. [CrossRef]

37. 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]
38. Li, Z.G.; Du, H.; Wang, Z.G.; Jin, C.Y.; Li, Y. Experimental investigation of MgAl-NO2 and MgAl-CO3 LDHs on durability of mortar and concrete. *Adv. Mater. Sci. Eng.* **2021**, *2021*, 5582150. [CrossRef]
39. Zheng, W.X.; Xiao, X.Y.; Wen, J.; Chang, C.G.; An, S.X.; Dong, J.M. Water-to-cement ratio of magnesium oxychloride cement foam concrete with caustic dolomite powder. *Sustainability* **2021**, *13*, 2429. [CrossRef]