



Article Influences of MgO and PVA Fiber on the Abrasion and Cracking Resistance, Pore Structure and Fractal Features of Hydraulic Concrete

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Abstract: Abrasion resistance and cracking resistance are two important properties determining the normal operation and reliability of hydropower projects that are subjected to erosion and abrasive action. In this study, polyvinyl alcohol (abbreviated as PVA) fiber and magnesium oxide expansive agents (abbreviated as MgO) were used together to solve the problems of cracking and abrasive damage. The effects of PVA fiber and MgO on the mechanical property, abrasion and cracking resistance, pore structures and fractal features of high-strength hydraulic concrete were investigated. The main results are: (1) The incorporation of 4–8% Type I MgO reduced the compressive strength, splitting tensile strength and the abrasion resistance by about 5–12% at 3, 28 and 180 days. Adding 1.2-2.4 kg/m³ PVA fibers raised the splitting tensile strength of concrete by about 8.5-15.7% and slightly enhanced the compressive strength and abrasion resistance of concrete. (2) The incorporation of 4-8% Type I MgO prolongs the initial cracking time of concrete rings under drying by about 6.5–11.4 h, increased the cracking tensile stress by about 6–11% and lowered the cracking temperature by 2.3–4.5 $^{\circ}$ C during the cooling down stage. Adding 1.2–2.4 kg/m³ PVA fibers was more efficient than adding 4-8% MgO in enhancing the cracking resistance to drying and temperature decline. (3) Although adding 4% MgO and 1.2-2.4 kg/m³ PVA fibers together could not enhance the compressive strength and abrasion resistance, it could clearly prolong the cracking time, noticeably increase the tensile stress and greatly lower the racking temperature; that is, it efficiently improved the cracking resistance to drying and thermal shrinkage compared with the addition of MgO or PVA fiber alone. The utilization of a high dosage of Type I MgO of less than 8% and PVA fiber of no more than 2.4 kg/m³ together is a practical technique to enhance the cracking resistance of hydraulic mass concretes, which are easy to crack. (4) The inclusion of MgO refined the pores, whereas the PVA fiber incorporation marginally coarsened the pores. The compressive strength and the abrasion resistance of hydraulic concretes incorporated with MgO and/or PVA fiber are not correlated with the pore structure parameters and the pore surface fractal dimensions.

Keywords: MgO; PVA fiber; abrasion resistance; cracking; pore; fractals

1. Introduction

The hydropower resource is abundant in the west and southwest of China [1,2]. Currently, large quantities of world-class hydraulic projects are being built in these regions of China [3]. These huge hydraulic projects are usually subjected to large amounts of water pressure (100–300 m water heat) and serious abrasive damage caused by the high-speed



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). water flow (50–100 m/s) containing sands and rocks during the water discharge [4,5]. Therefore, the hydraulic concretes in spillway, discharge tunnel and stilling basins are frequently abrasively damaged during operation, which greatly affect the normal operation and reliability of these hydropower projects [4,6]. Therefore, how to improve the abrasion resistance of concrete is an important issue in the construction of hydropower projects [3,7–9].

There are several methods to enhance the concrete abrasive resistance, e.g., optimization of surface finishing, utilization of high-strength concrete (by decreasing the water to binder ratio, or using silica fume and high-strength coarse aggregate), optimization of concrete mixtures and improvement of curing conditions, etc. [3,7-9]. Generally, the adoption of high-strength concrete is regarded to be the easiest and most effective one, because the abrasion resistance is linearly related to the compressive strength of concrete [6,10]. However, high-strength concrete with a low water-to-binder (W/B) ratio, or with the presence of silica fume, is very easy to shrink and crack, because such high-strength concrete usually has a high cement concentration that would increase the temperature and cause shrinkage as well as cracking problems [9,11]. The cracks in concrete could easily jeopardize the integrity of structures and worsen the abrasive damage, since the abrasive impact and the abrasive damage are more likely to take place around the cracks [6]. Moreover, most of the hydraulic concrete can be classified into mass concrete. The hydraulic mass concrete is susceptible to temperature rise and hence requires excellent cracking resistance [6,12]. Therefore, when designing the abrasion-resistant concrete for hydraulic mass structures, high strength is not enough, and the cracking resistance of concrete to drying and thermal shrinkage should be necessarily considered.

The utilization of polyvinyl alcohol (abbreviated as PVA) fiber and magnesium oxide expansive agent (abbreviated as MgO) are two commonly used methods to reduce the cracking risk of hydraulic concrete. The high-rigid PVA fibers in concrete act similar to the micro steel bar in order to suppress the generation and development of micro-cracks in the concrete, thus reducing the shrinkage and cracking risk of concrete [13-16]. The MgO manufactured by calcining magnesite magnesium has been utilized in hydraulic massive concrete during the past few decades [17,18]. The reaction between MgO and water tends to generate expansion, which could partially or completely compensate the shrinkage of concrete caused by drying or thermal stress [18–21]. According to DL/T 5296–2013 [22], MgO can be divided into two types in terms of reactivity. The first type is the reactive type, i.e., Type I MgO, with a neutralization time within 50–200 s. The second type is the weak reactive type, namely Type II MgO, with a neutralization time range of 200–300 s. Type I MgO could produce a fast expansion in cement mortar/concrete at early age (within 28 days), but a small final expansion [23,24]. Type II MgO, which mainly reacts with water at long-term hydration age, can be used to mainly compensate the longterm shrinkage [20,23,25]. It was reported that the MgO inclusion could slightly reduce the mechanical property of concrete, since the bonding property of the reaction product $Mg(OH)_2$ is weaker than C-S-H resulting from the cement hydration and thus negatively affects the concrete strength [26]. Zheng et al. [27] pointed that the utilization of MgO could refine the pore structures of concrete and consequently improve the impermeability property. Choi et al. [28] reported that the addition of 5 wt.% MgO improved the resistance of concrete to chloride permeability and negligibly affected the frost resistance of concrete.

Although there are many studies examining the influences of fiber and MgO on the shrinkage and cracking resistance of concrete, the studies on the influences of fiber and MgO on the abrasion resistance of hydraulic concretes have been rarely reported. Moreover, the synergetic effects of the combination of MgO and fibers on the mechanical properties and cracking resistance of concrete are unknown.

Due to the urgent need to improve the abrasion resistance and cracking resistance of hydraulic abrasion resistant concrete, in this study, the influence of PVA fiber and MgO on mechanical property, abrasion resistance, cracking resistance as well as the pore structures of high-strength hydraulic concrete were systematically investigated and compared. Fractal theory is a new branch of mathematics, resolving the irregularities, as well as the haphazard

phenomena and behaviors in nature [29–32]. Considering that fractal theory is a good method to study the pore structures and macro-performance of porous materials [33–35], the differences in the influences of PVA fiber and MgO on the concrete properties were revealed from the viewpoints of pore structure and fractal theory. The outcomes in this work may help engineers to design abrasion resistant concrete with small shrinkage and low cracking risk.

2. Materials and Analytical Methods

2.1. Materials

A commercial Portland cement with a 28-day compressive strength of 45.6 MPa, provided by Jiahua cement Co., China, was used in this study. The MgO with a reactivity of 150 s was used. The MgO adopted in this work can be categorized as Type I MgO. Considering that the cracking risk of high-strength concrete is relatively high at early early, Type I MgO which could generate a quick expansion at early age was utilized in this work. The silica fume, provided by Guizhou Haitian Co., Guizhou, China, was used to produce the high-strength hydraulic concrete. The chemical oxides and physical properties of cement, silica fume and MgO are shown in Table 1. The PVA fiber, provided by Shuangxin New Material Co., China, was adopted in this work. The physical properties of PVA fibers are listed in Table 2.

Table 1. The chemical oxides and physical property of cement, silica fume and MgO.

Oxide (%)	Cement	Silica Fume	MgO
Chemicals			
CaO	61.3	1.4	2.6
SiO ₂	19.3	94.4	1.5
Fe ₂ O ₃	4.3	1.2	0.6
Al_2O_3	4.7	0.8	0.1
MgO	3.7	0.6	90.6
SO_3	2.6	-	0.2
Loss on ignition (%)	1.20	0.75	3.1
Specific gravity	3.19	2.04	3.52
Blaine specific surface area (m ² /kg)	326	-	-
BET specific surface area (m^2/g)	0.89	16,500	20.40

Table 2. Physical properties of PVA fibers.

Length	Diameter	Density	Tensile Strength	Elastic Modulus
(mm)	(µm)	(g/cm ³)	(MPa)	(GPa)
20	30	1.30	1538	36

Granite samples with a density of 2890 kg/m³ were crushed and manufactured into coarse and fine aggregates. Based on Chinese standard DL/T 5330 [36], the hydraulic concrete is featured by the adoption of coarse aggregate with a relatively large particle size. For example, for two-graded concretes, the maximal particle size is 40 mm, and the coarse aggregate size can be divided into two grades: 5–20 and 20–40. For three-graded concrete, the maximal particle size is 80 mm, and the coarse aggregate size can be divided into three grades: 5–20, 20–40 and 40–80 mm. In this work, the two-graded concrete was prepared. The weight ratio of 5–20 mm aggregate to 20–40 mm aggregate is 4:6. The fineness modulus of fine aggregate is 2.71. The aggregates were maintained at a saturated surface dry (SSD) state before they were used to mix concrete. The sieve results of the fine and coarse aggregates are shown in Figure 1, which indicates the grain size distribution of the aggregates.



Figure 1. Sieve analysis of (a) fine aggregate and (b) coarse aggregate used in this study.

2.2. Mix Proportion Design

The mix proportions of hydraulic concrete, as exhibited in Table 3, were designed using the volume method specified in DL/T 5330 (Code for mix design of hydraulic concrete) [36]. Seven concrete mixtures were used in this study. Silica fume was used in all of the concrete mixtures in this study at a dosage of 6%, by weight of binder, to produce high strength concrete. The W/B ratio is maintained at 0.33, which is within the normal range of 0.30–0.35 for producing high-strength concrete in practice. In some real engineering projects, the recommended MgO dosage range is 4–8% [18]. Hence, two MgO dosages (4% and 8% by weight of binder) were used. PVA fiber was added to concrete at two levels, 1.2 kg/m³ and 2.4 kg/m³, which can be converted to about 0.1% and 0.2% by volume of concrete. Higher content of PVA fiber was not adopted in this study since the fiber addition beyond 0.2% by volume of concrete tended to produce balling of fibers and workability problems of concrete mixture [37]. The polycarboxylate-based water reducer was adopted at a dosage range of 0.6–1.0% to maintain the concrete slump at about 50 mm.

	W/B	Mix Proportions (kg/m ³)								
Notation Ratio	Ratio	Water	Cement	Silica Fume	MgO	Sand	Coarse Aggregate	Fiber	Water- Reducer	Slump
CT0	0.33	123	350	22	0	642	1428	0	2.24	55
CSM4	0.33	123	335	22	15	642	1429	0	2.61	53
CSM8	0.33	123	320	22	30	642	1430	0	2.98	51
CSP2	0.33	123	350	22	0	642	1428	1.2	2.98	54
CSP4	0.33	123	350	22	0	642	1428	2.4	3.35	52
CSM4P2	0.33	123	335	22	15	642	1429	1.2	3.72	52
CSM4P4	0.33	123	335	22	15	642	1429	2.4	3.72	50

Table 3. Mix proportion and notation of hydraulic concrete added with MgO and/or PVA fiber.

A control concrete mixture, CT0, was designed to have a compressive strength about 55 MPa at 28 days. The concretes added with 4% and 8% MgO were named after "CSM4" and "CSM8", respectively. The concretes containing 1.2 kg/m³ and 2.4 kg/m³ PVA fibers were designated as "CSP2" and "CSP4", respectively. Besides, in order to study the synergy effect of MgO and PVA fiber on concrete properties, the MgO and PVA fiber were added together into concrete. "CSM4P2" refers to the concrete mixture added with 4% MgO and 1.2 kg/m³ PVA fiber. "CSM4P2" refers to the concrete incorporated with 4% MgO and 2.4 kg/m³ PVA fiber. "CSM4P4" denotes the concrete incorporated with 4% MgO and 2.4 kg/m³ PVA fiber. Noticeably, the inclusion of MgO and/or PVA fibers would reduce the workability of concrete, Table 3 indicates that a larger amount of water-reducer was utilized to obtain the same target slump value compared with other mixtures without MgO and/or PVA. This experimental phenomenon is widely reported since the fine MgO particles and fibers would absorb the mixture water.

2.3. Test Methods

2.3.1. Mechanical Property of Concrete

The compressive and splitting tensile strengths of hydraulic concretes were tested at 3, 28 and 180 days in accordance with DL/T 5150 [38]. The samples with a size of 150 mm \times 150 mm \times 150 mm were utilized for the compressive and splitting tensile strength tests. After being demolded, the concrete samples were cured in a foggy room (20 \pm 2 °C and RH larger than 95%). For each concrete mixture, six samples with the same hydration age were determined to obtain an average compressive strength result, and three samples were tested to obtain an average splitting tensile strength result.

2.3.2. Abrasion Resistance Tests

The abrasion resistance of hydraulic concrete was tested at 3, 28 and 180 days, following the underwater method specified in DL/T 5150 [38]. The testing procedure of this method is similar with that described in ASTM C1138 [39]. The underwater method test machine was shown in Figure 2a, and the abrasively damaged concrete specimen was shown in Figure 2b. For each concrete mixture hydrated at the same age, three cylindrical samples with a diameter of 30 cm and a thickness of 10 cm were tested. During the test, the surfaces of specimens were subjected to the grinding and abrasive action of the steel balls (ranging from 12.7 to 25.4 mm in diameter) driven by the high-speed circulating water in the abrasion test machine. The water was circulated by a paddle rotator with a speed of 1200 revolutions per minute. After 72 h of abrasion, the mass loss of each specimen was measured. Then, the abrasion resistance strength of concrete (f) was determined by Equation (1):

$$= TA/\Delta M$$
 (1)

where f is the abrasion resistance strength, $h \cdot m^2/kg$; T is the abrasion time, 72 h; A is the surface area of the specimen, which equals to 225 cm²; Δm is the mass loss of specimen after the test, kg. The average abrasion resistance strength of three specimens was reported.

F



Figure 2. Abrasion resistance test: (a) the underwater method instrument and (b) the abrasively damaged concrete specimen.

2.3.3. Cracking Resistance

The Restrained Concrete Ring Test

The restrained concrete ring test was conducted according to ASTM C 1581 [40]. This method was widely adopted to assess the cracking risk of concrete at early age caused by the restrained drying shrinkage [41].

The thickness, outer diameter and inner diameter of the concrete rings are 15.2 cm, 40.6 cm and 33 cm, respectively. The test specimens were schematically shown in Figure 3.

Before the tests, the fresh concrete was put into the steel moulds. After 24 h of curing, the ring samples were demouled with the exception of the inner steel rings. Subsequently, the top surfaces and the bottom surfaces of the concrete rings were painted fully with paraffin; as a consequence, the evaporation of water only occurred on the outer circumferential surfaces of the concrete rings. Then, the concrete rings were stored in a drying room maintained at 20 ± 0.3 °C and $50 \pm 3\%$ RH. During the restrained drying shrinkage test, three concrete rings were tested for each concrete proportion. Under the strong evaporation environment, the drying shrinkage of the samples is completely constrained by inner steel ring. Once the restrained shrinkage-induced tensile stress is larger than the tensile strength, concrete rings would crack [37,41]. The average initial cracking time of three rings for each concrete proportion was determined.



Figure 3. The restrained concrete rings: (a) the ring before demoulding and (b) the ring being test.

The Temperature Stress Test Machine (TSTM) Test

In this study, TSTM is the second method to assess the cracking risk of hydraulic concrete. TSTM instrument provides different degrees of restraint and an adiabatic environment, simulating the actual working conditions of the mass concretes, and thus it could be adopted to evaluate the cracking risk caused by temperature stress [18].

In this study, the TSTM instrument from "Walter + Bai" company, Löhningen, Switzerland was adopted. The test procedure followed the introduction of RILEM TC 119 [42]. Before the test, the machine chamber was covered by a plastic film to prevent water loss and the frictional constraints on concrete specimens. Then, the fresh concrete was cast into the machine chamber to form a cubic concrete specimen with a size of $15 \text{ cm} \times 15 \text{ cm} \times 150 \text{ cm}$. The whole chamber was maintained in a semi-adiabatic condition to make sure there is no thermal exchange between concrete specimen and instrument. This can be conducted by keeping the liquid medium within the chamber pipes at the same temperature as the internal concrete sample. Moreover, two ends of the specimen were fixed to prevent any displacement and length change of the concrete specimen in the test, providing a complete constrained condition. When the test started, the temperature of the internal specimen would increase due to the cement hydration. The temperature and compressive stress developments of the specimen in a completely constrained and semi-adiabatic conditions were recorded every 5 min. Once the peak temperature of the concrete specimen appeared, it was kept for 3 days. Then, the specimen was cooled down at a rate of $5 \,^{\circ}C/h$ by circulating the cool liquid medium inside the machine. As a result, the thermal stress rapidly developed inside the specimen until the thermal cracking appeared. The cracking temperature (T_c) and cracking time were recorded. Moreover, there are several other important parameters obtained from the TSTM experiments which can be utilized to assess the cracking risk of concretes, as listed in Table 4.

Parameter	Physical Meanings
First Zero stress temperature $T_{Z,1}$	Under restrained condition, the temperature at which the compressive stress firstly occurs due to the generation of hydration heat
Maximum compressive stress $\sigma_{c,max}$	The maximum compressive stress due to cement hydration or concrete expansion under restrained condition.
Maximum temperature T _{max}	The peak temperature of concrete sample due to cement hydration.
Second Zero stress temperature $T_{Z,2}$	The temperature at which the compressive stress reduces to zero and tensile stress begins to develop during the cooling stage.
Cracking tensile stress σ	The maximum tensile stress corresponding to the occurrence of specimen cracking in the cooling stage.
Cracking temperature T _c	The temperature corresponding to the sample cracking in the cooling stage.

Table 4. Temperature parameters from TSTM test and their concepts specified in Standard [42].

2.3.4. Pore Structure Test

The pores in concrete are considered to affect the mechanical properties of concrete significantly. In this study, the pore structure parameters such as porosity, pore size distribution and critical pore diameter of hydraulic concrete hydrated at 3, 28 and 180 days were evaluated by a mercury intrusion porosimeter (MIP, AutoPore IV 9500 model, Micromeritics instrument company, Norcross, GA, USA). This porosimeter could measure the pores in concrete with a pore diameter range of $2 \text{ nm}-10 \mu\text{m}$. The MIP samples were small pieces with a size of about 5 mm. These small pieces were cut from the middle part of the concrete samples used for mechanical property tests. Before the test, the coarse aggregate particles were removed from the small pieces to prevent the coarse aggregate effects on the accuracy of the test results. For each MIP test, four small pieces were put into the 5 mL glass tube, in order to minimize the influence of sample variations on the test results.

2.3.5. Fractal Dimension Calculation

Many studies [43–45] confirmed that the fractals can be used to study the microstructures and the macro-performance of concrete. For instance, the pore structures of concrete are complex and heterogeneous, the fractal geometry can characterize and evaluate the roughness and complexity of pores very well. The fractal dimension, the key parameter in fractals, has been proven to be closely related with the concrete properties [46,47]. Many fractal models have been developed to determine the fractal dimensions, including the Zhang's fractal model [48] which based on the MIP results. In this work, the Zhang's fractal model was used to calculate the fractal dimension of pore surface (D_s) of face slab concrete. The fundamental of this model is that the accumulated injection work on mercury (W_n) is logarithmically correlated with the total injected mercury volume (V_n) during the MIP test, which is described by Equation (2):

$$\ln \frac{W_{\rm n}}{r_{\rm n}^2} = D_{\rm s} \ln \frac{V_{\rm n}^{1/3}}{r_{\rm n}} + C \tag{2}$$

where r_n refers to the pore radius, m; n means the n-th mercury injection, C represents a regression constant.

 W_n can be determined by Equation (3):

$$W_{\rm n} = \sum_{i}^{\rm n} p_i \bigtriangleup V_i \tag{3}$$

where the index *i* refers to the *i*-th mercury injection, which is between 1 and n; p_i denotes the mercury pressure, Pa; V_i represents the injected volume of mercury at the *i*-th injection, m³.

The values of W_n , V_n , $\ln \frac{W_n}{r_n^2}$ and $\ln \frac{V_n^{1/3}}{r_n}$ can be determined by using the MIP results and Equation (3). Then, D_s , which is the slope of the straight line in Equation (1), can be calculated by Equation (2).

3. Results and Discussion

3.1. Mechanical Properties of Hydraulic Concretes

The mechanical properties of hydraulic concretes added with MgO and/or PVA fiber are shown in Figure 4. Figure 4 shows that the MgO and PVA fiber have different impacts on the mechanical properties of hydraulic concretes.



Figure 4. (a) Compressive strength and (b) splitting tensile strength of hydraulic concretes added with MgO and/or PVA fiber.

Regarding the effects of MgO addition, Figure 4 exhibits that the addition of 4–8% MgO reduced the compressive strengths by 8.6–14.1%, 6.5–11.7% and 4.9–10.4% at 3, 28 and 180 days, and lowered the splitting tensile strengths by 7.9–15.2%, 7.2–12.4% and 5.4–11.1% at 3, 28 and 180 days, respectively. Moreover, Figure 4 shows that the larger MgO dosage, the more noticeable reduction in concrete mechanical properties. These findings are consistent with those reported by others [49,50]. There are several reasons # for this reduction: (1) The reduced amount of cement due to the MgO addition would result in a smaller quantity of hydration product such as C-S-H that determines the mechanical properties of concrete [50–52]. (2) The generation of Mg(OH)₂ crystals (brucite) resulting from the reaction between MgO and H₂O would reduce the strengths of concrete, since brucite exhibits no bonding property at all and it is considered to be weaker than C-S-H [26]. (3) The enlarged porosity and formation of micro-cracks due to brucite expansion could also reduce the concrete mechanical properties [51].

In addition, a careful examination of the data in Figure 4 indicates that the mechanical properties of CSM4 and CSM8 concretes were slightly enhanced at 180 days. For example, the CSM4 concrete shows an 8.6% smaller compressive strength than the CT0 concrete at 28 days, whereas this gap is reduced to 4.9% at 180 days. The similar findings was reported by Choi et al. [28], who proposed that the concrete added with 5% MgO with a reactivity of 210 s had a comparable compressive strength with the control concrete at 180 days. They summarized that the expansion caused by MgO optimized the pore structure of concrete at 180 days and hence enhanced the concrete strength. Cao et al. [26] also reported that the reaction of MgO at middle and long-term hydration time densified the porous structures and enhanced the concrete strengths.

Regarding the effects of the PVA fiber, Figure 4 clearly shows that the addition of $1.2-2.4 \text{ kg/m}^3$ (namely, 0.1-0.2% by volume of concrete) PVA fiber is beneficial for the enhancement of compressive strength and splitting tensile strength of CSP2 and CSP4

concretes, especially for the splitting tensile strength. Specifically, the presence of 1.2 kg/m³ PVA fiber raised the compressive strength of CSP2 concrete by about 2.5%, 2.2% and 2.9% at various hydration ages, whereas it increased the splitting tensile strength by about 9.1%, 8.9% and 8.5% at 3, 28 and 180 days, respectively. Much stronger enhancement of splitting tensile strength, viz., 15.7%, 15.2% and 14.8% at 3, 28 and 180 days, respectively, can be observed for CSP4 concrete when comparing with CT0 concrete. These findings correspond well with the data from prior studies [53,54],which revealed that the addition of fibers below a volume fraction of 0.25% favored the improvement of tensile strength and compressive strength. It is interesting to note that the fiber dosage utilized in this study is within their recommended level. The notable enhancement of splitting tensile strength in the presence of fibers is because the uniformly distributed PVA fibers in concrete can act as micro steel bars to transfer the tensile stress and inhibit the formation and development of small cracks in the concrete, leading to a stronger tensile capacity [37]. The other reason is that there are many hydroxyl groups in the molecular chains of PVA fibers, producing a strong chemical bonding between PVA fiber and cement matrix [55].

Furthermore, the synergy effect of MgO and PVA fiber on concrete mechanical properties can be obtained from Figure 4. CSM4P2 and CSM4P4 concretes added with MgO and PVA fibers together exhibited comparable compressive strengths with the CT0 one, and presented slightly larger splitting tensile strengths than CT0 concrete. This is because the negative effects of MgO on concrete mechanical properties would be offset by the positive effects of PVA fibers.

3.2. Abrasion Resistance

Table 5 shows the abrasion resistance results of hydraulic concretes added with MgO and/or PVA fiber hydrated at 3, 28 and 180 days. The enhanced degrees of abrasion resistance of concretes containing MgO and/or PVA fiber over CT0 concrete are also exhibited in Table 5. Table 5 clearly displays that the MgO and PVA fiber inclusion have different effects on abrasion resistance of concretes.

	W/B Ratio	Abrasion Resistance of Concrete						
Notation		f (h·m²/kg)			Enhanced Degrees (%)			
	_	3-Day	28-Day	90-Day	3-Day	28-Day	90-Day	
CT0	0.33	7.7	11.9	15.6	0.0	0	0	
CSM4	0.33	7.3	11.1	14.8	-5.7	-6.8	-5.4	
CSM8	0.33	6.9	10.4	13.9	-11.2	-12.5	-11.1	
CSP2	0.33	8.0	12.4	16.3	3.6	3.9	4.2	
CSP4	0.33	8.2	12.7	16.8	5.8	7.1	7.5	
CSM4P2	0.33	7.5	11.6	15.3	-2.5	-2.8	-1.9	
CSM4P4	0.33	7.8	12.1	16.0	1.0	1.3	2.5	

Table 5. The abrasion resistance of hydraulic concretes added with MgO and/or PVA fiber.

Also, the correlation between the abrasion resistance and compressive strengths of hydraulic concretes is shown in Figure 5, which shows that the abrasion resistance is linearly correlated with the compressive strength of hydraulic concretes in this study, and the correlation coefficient (R^2) approaches 1.0. As reported by other studies [6,10], the concrete abrasion resistance mainly depends on compressive strengths of concrete, and the high compressive strength enhances the resistance of concrete to abrasive action.

As shown in Table 5, the MgO inclusion negatively affected the abrasion resistance. The inclusion of 4–8% MgO reduced the abrasion resistance by approximately 5.7–11.2% at 3 days, 6.8–12.5% at 28 days, and 5.4–11.1% at 180 days. Clearly, a higher MgO dosage led to a larger reduction in abrasion resistance. This is because the compressive strength of the concrete was weakened due to the MgO inclusion, as revealed in Figure 5, the low compressive strength tended to weaken the abrasion resistance of concrete.



Figure 5. The correlation between abrasion resistance and compressive strength of hydraulic concretes.

Table 5 also indicates that the addition of $1.2-2.4 \text{ kg/m}^3$ PVA fiber enhanced the abrasion resistance of concrete. Specifically, the CSP2 concrete and CSP4 concrete showed enhancement in abrasion resistance of 3.6% and 5.8% at 3 days, 3.9% and 7.1% at 28 days, 4.2% and 7.5% at 180 days over CT0 one, respectively. Similar enhancements in abrasion resistance associated with fiber addition have been reported elsewhere [5,8,56]. This enhancement is mainly due to the increase in the compressive strength of concrete caused by PVA fiber inclusion. There are also other mechanisms responsible for these enhancements: (1) The friction work could be consumed when steel or polymetric fibers are pulled out from concrete under the abrasive action [56]. (2) The crack arresting effect and the bridge effect of fibers work together to delay the abrasion damage process and consequently enhance the abrasion resistance of concrete [5]. Moreover, Horszczaruk pointed out that the larger the fiber content, the stronger these effects are [8].

Table 5 also shows that the abrasion resistance of CSM4P2 and CSM4P4 concretes were almost the same with that of CT0, indicating that adding 4% MgO and 1.2–2.4 kg/m³ PVA fiber together would not enhance the abrasion resistance of concrete. This trend is in line with the mechanical strengths above. The mechanism behind is that the MgO and PVA fiber have two opposite effects on the abrasion resistance of concrete, and the positive effects of PVA fibers on abrasion resistance would be partially eliminated by the negative effect of MgO. In this regard, it seems that adding MgO alone is not a good means to enhance the abrasion resistance of concrete.

3.3. Cracking Resistance of Concrete

3.3.1. The Restrained Concrete Ring Test Results

The initial cracking time of hydraulic concretes added with MgO and/or PVA fiber determined by the concrete ring test is exhibited in Figure 6. During this experiment, the drying shrinkage of concrete rings was restrained by the steel rings, resulting in the formation of tensile stress. If the tensile stress exceeds the tensile strength, cracks of the rings would be generated. Therefore, the cracking time of concrete rings can be adopted to assess the cracking risk [41]. Figure 6 shows that the inclusion of MgO and/or PVA fiber could prolong the initial cracking time of concretes rings.

As for the effects of MgO, Figure 6 shows that the addition of 4% and 8% MgO prolongs the initial cracking time by about 6.5 h and 11.4 h over the CT0 concrete, respectively, demonstrating that the MgO addition obviously enhances the cracking resistance. The same finding was evidenced by Mo et al. [57], who reported that Type I MgO with a reactivity of 47 s reacted rapidly and subsequently produced significant expansion. Other researchers also reported that the MgO inclusion could lower the drying shrinkage development and reduce the cracking risk during the initial several days of hydration [20,52]. The

reason behind is that the reaction of MgO could generate lots of $Mg(OH)_2$ crystals, the expansion of which is expected to compensate the shrinkage and suppress the generation of concrete cracks [19]. Additionally, this expansion would occur with an increase in the MgO dosage [20,52].



Figure 6. The initial cracking time of hydraulic concretes added with MgO and/or PVA fiber.

Regarding the effects of PVA fibers on the cracking resistance of concrete to drying shrinkage, Figure 6 indicates that the inclusion of 1.2 kg/m³ and 2.4 kg/m³ PVA fibers delay the initial cracking time of CT0 concrete by 12.6 and 20.5 h, respectively, suggesting that the PVA fiber-enhanced concretes, namely, CSP2 and CSP4, exhibit excellent cracking resistance. Similar experimental results were reported by Yousefieh et al. [37]. They reported that steel fibers, polypropylene fibers and polyolefin fibers could raise the cracking strain and result in a longer time to bear stress before cracking. The good cracking resistance of PVA fiberenhanced concrete in this study can be explained by the following two possibilities. The first one is that the incorporation of PVA fibers with high elastic modulus and tensile strength obviously eases the shrinkage development and reduces the cracking risk of concrete [37]. The second is that the high hydrophilic property of PVA fibers usually produces good adherence of fibers with cement matrix, which could suppress the formation of shrinkage cracks [53,54]. It is interesting to note that CSP2 and CSP4 concretes exhibit longer initial cracking times than the CSM4 and CSM8 concretes, suggesting that adding 1.2–2.4 kg/m³ PVA fibers was more efficient than adding 4–8% MgO in improving the cracking resistance to restrained drying.

Figure 6 also displays that the concretes containing MgO and PVA fiber together exhibit longer initial cracking time than other concrete mixtures in this work. To be specific, the initial cracking time of CSM4P2 and CSMP4 are 21.6 h and 29.4 h longer than that of CT0, respectively. Moreover, CSMP4 concrete exhibits 18.0 h and 8.9 h longer initial cracking time than CSM8 and CSP4, respectively. Similarly, Figure 6 also shows that CSMP2 concrete exhibits longer initial cracking time than that the concretes containing solely MgO and PVA fiber. These results clearly indicate that adding 4% MgO and 1.2–2.4 kg/m³ PVA fiber together is more efficient in improving the cracking resistance of concrete to drying than by adding 4–8% MgO or 1.2–2.4 kg/m³ PVA fiber alone. This finding is probably due to the fact that MgO and PVA fiber can work together to mitigate the drying shrinkage development and improve the cracking resistance to restrained drying.

Considering the facts that the drying shrinkage of concretes mainly develops at early hydration age and the cracking risk is relatively high at early age when the tensile strengths of concrete is low, the MgO and PVA fiber should be used together in practice to enhance the cracking resistance of hydraulic concretes.

3.3.2. TSTM Test Results

In spite of the restrained drying-shrinkage-induced stress, the hydraulic mass concretes are commonly subjected to the thermal stress caused by the temperature decline and the subsequent thermal cracking. Therefore, it is important to study the influences of MgO and PVA fibers on the cracking resistance of hydraulic mass concretes to the thermal stress.

The key temperature stress parameters of hydraulic concretes added with MgO and/or PVA fiber determined by the TSTM tests are shown in Table 6. A typical example of TSTM curves of the CT0, CSM8, CSP4 and CSM4P4 concretes is given in Figure 7. It can be seen from Figure 7 that, these four concrete specimens present similar thermal stress behavior, i.e., the compressive stresses raised as the internal concrete temperature increased, until the maximum temperature T_{max} was reached. During the subsequent cooling down period, the compressive stresses rapidly dropped to zero and the tensile stress started increasing to a peak value σ when the cracking occurred.

Figure 7 and Table 6 clearly display that both the MgO and fiber addition notably affect the thermal stress parameters, including the cracking tensile stress σ , cracking temperature T_c and the maximum compressive stress $\sigma_{c,max}$. As proposed by RILEM TC119 [42], T_c and σ are two controlling factors affecting the cracking resistance to thermal stress. Specifically, the high σ and low T_c vaules imply good cracking resistance. Other studies reported that the high $\sigma_{c,max}$ value favors the compensation of the thermal stress [18,58].



Figure 7. A typical example of TSTM curves of the CT0, CSM8, CSP4 and CSM4P4 concretes: (a) the internal temperature development and (b) the maximum compressive stress $\sigma_{c,max}$, cracking tensile stress σ and cracking temperature T_c development.

Notation	1st Zero Stress Temperature T _{Z,1} (°C)	Maximum Compressive Stress σ _{c,max} (MPa)	Maximum Temperature T _{max} (°C)	2nd Zero Stress Temperature T _{Z,2} (°C)	Tensile Strength σ (MPa)	Cracking Temperature T _c (°C)
CT0	28.1	0.26	64.8	55.7	0.89	13.8
CSM4	27.8	0.30	62.4	53.2	0.94	11.5
CSM8	27.6	0.34	60.3	51.5	0.98	9.3
CSP2	27.8	0.26	64.1	56.1	0.96	8.5
CSP4	27.9	0.26	63.9	56.6	1.03	3.4
CSM4P2	27.7	0.30	62.4	53.0	1.04	5.4
CSM4P4	27.8	0.30	62.5	52.8	1.09	-1.5

Table 6. The key temperature stress parameters of hydraulic concretes added with MgO and/or PVA fiber.

As for MgO, the results in Figure 7 and Table 6 indicate that the addition of MgO at dosages of 4% and 8% increased the $\sigma_{c,max}$ value from 0.26 MPa for CT0 concrete to 0.30 and 0.34 Mpa, increased by about 15% and 31%, respectively, during the temperature rising stage. This finding evidently confirmed that MgO in this study reacted with water and produced a large expansion at the early hydration age. This experimental result is supported by other study [25], in which the compacted pure MgO powders with a reactivity of 71 s produced a great amount of expansion stress when it touched water. The high $\sigma_{c,max}$ value in concrete is beneficial to eliminate more thermal stress during cooling period, in other words, to bear high cracking tensile stress σ and large temperature declines before cracking [18,58]. Besides, CSM4 and CSM8 concretes exhibited σ and T_c vaules of 0.94 MPa and 0.98 MPa, 11.5 °C and 9.3 °C, which are 6% and 11% larger, 2.3 °C and 4.5 °C lower than those of CT0 one, respectively, illustrating that the MgO addition enhanced the cracking resistance of concrete during the temperature drop. These results correspond well with the restrained concrete ring test results above and other similar TSTM results [21]. For example, Chen et al. [21] found that the incorporation of 4% Type I MgO (59 s) increased the $\sigma_{c,max}$ and σ by about 32% and 12%, respectively, and reduced the T_c by 1.5 °C. Also, they pointed out that the further increase in MgO dosage to 6% led to larger $\sigma_{c,max}$ and σ values, as well as a lower T_c .

Regarding the influence of PVA fiber on the cracking resistance of concrete to thermal stresses, it can be found from Table 6 that, the CSP2 and CSP4 concretes presented quite similar thermal stress indexes ($T_{Z,1}$, $T_{Z,2}$, $\sigma_{c,max}$ and T_{max}) with the CT0 concrete. Furthermore, from Figure 7, the temperature stress curves of CSP4 and CT0 concrete are overlapped during the temperature rise stage. This phenomenon is due to the same binder amount when PVA fiber was used in this study. As exhibited in Table 4, CT0, CSP2 and CSP4 mixtures have the same binder amount. It was reported that the indexes $T_{Z,1}$, $T_{Z,2}$, $\sigma_{c,max}$ and T_{max} are determined mainly by the binder amount used in mixtures [21]. During the subsequent cooling down period, Table 6 shows that the inclusion of $1.2 \text{ kg/m}^3 \text{ PVA}$ fiber raised the σ value of CT0 concrete by about 8% and reduced the T_c by about 5.3 °C. As the PVA fiber content increased to 2.4 kg/m³, the σ value of CT0 concrete was increased by about 16% and the T_c value of CT0 was lowered by about 10.4 °C, suggesting that the PVA fiber can enhance the cracking resistance to thermal stress. This finding is consistent with the splitting tensile strength trend in Section 3.1 and the restrained concrete ring result in Section 3.3.1 as well as the TSTM findings revealed by Ref. [59]. As discussed above, the PVA fibers can transfer the tensile stress by the bridge effect and thus providing strong bridging force to inhibit the crack formation, which make the concrete bear high thermal tensile stress and possess good cracking resistance. In addition, Table 6 shows that the CSP2 and CSP4 concretes exhibit larger σ values and lower T_c values than the CSM4 and CSM8 ones, demonstrating that the inclusion of 1.2–2.4 kg/m³ PVA fibers exhibited better efficiency in enhancing the cracking resistance to thermal stress than the inclusion of 4–8% MgO, which corresponds well with the restrained concrete ring results above.

Moreover, Table 6 shows that the incorporation of MgO and PVA fiber together is more effective to enhance the cracking resistance of concrete to thermal stresses than by adding MgO or PVA fiber alone. For instance, among all of the concrete mixtures in this study, CSM4P4

concrete exhibited the largest σ value of 1.09 MPa, which is 13.5% and 5.8% larger than the CSP2 concrete and CSP4 concrete, respectively, and 15.9% and 11.2% larger than the CSM4 concrete and CSM8 concrete, respectively. Moreover, CSM4P4 concrete exhibits the lowest T_c value of -1.5 °C, which is 10 °C and 4.9 °C lower than the CSP2 concrete and CSP4 concrete, respectively, and 13.0 °C and 10.8 °C lower than the CSM4 concrete and CSM8 concrete, respectively. Similarly, CSM4P2 concrete also exhibited lower Tc values and larger σ values than the concretes added with MgO or PVA fiber alone. The results above evidently confirm that by adding 4% MgO and 1.2–2.4 kg/m³ PVA fiber together, much better cracking resistance of concrete to thermal stress can be obtained by adding 4–8% MgO or 1.2–2.4 kg/m³ PVA alone. This finding is consistent with the restrained concrete ring result above. This is because adding MgO and PVA fiber together can not only increase the $\sigma_{c,max}$ value due to the Mg(OH)₂ expansion, but also raise the σ value and reduce the T_c value in the presence of PVA fibers.

On the basis of the restrained concrete ring and TSTM results above, the CSM4P2 and CSM4P4 concretes exhibited better cracking resistance to the restrained drying shrinkage and the thermal stresses. Clearly, the utilization of high dosage of Type I MgO and PVA fiber together is a practical technique to enhance the cracking resistance of hydraulic mass concretes to shrinkage caused by drying and temperature drop. Nevertheless, the optimal MgO and PVA fiber content adopted in practical hydraulic mass concretes should be experimentally determined. Some reasonable recommendation could be still made, that is, the dosage of Type I MgO should be limited below 8% to avoid significant reduction in mechanical property and abrasion resistance, the PVA fiber content should be no more than 2.4 kg/m³ to prevent the workability problems.

3.4. MIP Results

Table 7 shows the pore structure parameters of hydraulic concrete incorporated with MgO and/or PVA fiber hydrated at 3, 28 and 180 days, including the critical pore diameter, porosity and the pore size distribution. The classical method proposed by Mindess et al. [60] was adopted in this study: pores with a size range of 2.5–10 nm, 10–50 nm, and 50 nm–10 μ m can be classified into small capillary(or gel) pores, medium capillary pores and large capillary pores, respectively. Table 7 indicates that the presences of MgO and PVA fiber have different effects on the pore structure development.

As shown in Table 7, the inclusion of MgO refined the pores of CT0 concrete at various hydration times, and this refinement effect enhanced with raising MgO dosage from 4% to 8%. In the case of CSM8 concrete, the 8% MgO addition reduced the 3-day, 28-day and 180-day porosity from 28.3%, 21.5% and 19.1% for CT0 concrete to 22.5%, 15.7% and 14.3% for CSM8 one, respectively. Meanwhile, the 3-day, 28-day and 180-day fractions of large capillary pores (shortened as $V_{50 nm-10 \mu m}$ thereafter) were reduced from 66.8%, 42.8% and 26.2% for CTO concrete to 59.8%, 36.6% and 18.2% for CSM8 one, respectively. This trend is similar to that proposed by Mo et al. [49], who reported that the incorporation of 8% Type I MgO with a reactivity of 45 s lowered the porosity of cement pastes. This pore refinement effect of MgO is because that the reactive Type I MgO could quickly react to form lots of $Mg(OH)_2$ to fill the pores. Moreover, Mg(OH)₂ crystals tend to grow and generate great expansion which could refine and densify the pore structures of cement pastes and concretes [19]. It is also worth mentioning that the addition of 4–8% Type I MgO cannot clearly change the proportions of small capillary (gel) pores. This finding can be explained by the fact that the proportion of small capillary (gel) pores was mainly associated with the amount of the dominate hydration product C-S-H gel, while the addition of MgO could not affect the C-S-H amount and thus would not raise the proportions of small capillary (gel) pores.

Different from the refinement effect of MgO, Table 7 shows that the fiber incorporation slightly coarsened the pore structure of concrete at various hydration time. As for CSP4 concrete cured at 3 days, the critical pore diameter, porosity and $V_{50 \text{ nm}-10 \mu m}$ are 227 nm, 35.1% and 72.9%, which were 64 nm, 6.8% and 6.1% larger than those of CT0 one, respectively. The similar pore-coarsening effect was reported in prior studies [53,55]. Nam et al. [53] proposed that the inclusion of PVA and/or PP fibers raised the proportions of pores ranged

from 0.1 to 10 μ m in mortar. Sahmaran et al. [55] found that the PVA fiber addition significantly raised the porosity; moreover, the fractions of the pores ranged from 0.30 to 2 μ m in diameter in engineered cementitious composites (ECC). However, the mechanism to explain this pore-coarsening effect has not been revealed thus far; therefore, further research should be carried out regarding this issue, which is beyond the scope of the present paper.

Notation	Curing Time	Critical Pore	Porosity	Pore Size Distribution			
ivotation	(Days)	Diameter (nm)	(%)	<10 nm (%)	10–50 nm (%)	50 nm–10 μm (%)	
	3	162	28.3	7.5	25.5	66.8	
CT0	28	70	21.5	13.4	43.5	42.8	
	180	41	19.1	19.5	54.1	26.2	
	3	147	25.4	7.3	29.3	63.2	
CSM4	28	60	18.6	13.0	46.1	40.5	
	180	33	17.2	19.1	58.3	22.2	
	3	123	22.5	7.1	32.6	59.8	
CSM8	28	49	15.7	12.7	50.2	36.6	
	180	26	14.3	18.7	62.8	18.2	
	3	196	32.5	7.3	22.4	69.6	
CSP2	28	93	25.3	13.1	38.9	47.6	
	180	65	21.5	18.6	51.3	29.7	
	3	227	35.1	7.1	19.6	72.9	
CSP4	28	116	28.6	12.7	35.8	50.8	
	180	86	23.6	18.3	48.1	33.1	
	3	165	28.6	7.3	26.2	66.1	
CSM4P2	28	72	21.6	13.0	42.9	43.7	
	180	43	18.9	18.9	55.2	25.6	
	3	191	30.8	7.2	23.9	68.6	
CSM4P4	28	91	24.2	12.8	40.3	46.3	
	180	63	20.8	18.7	52.6	28.3	

Table 7. Pore structures of hydraulic concretes containing MgO and/or PVA fiber.

When the MgO and PVA fibers were added together, Table 7 shows that the CSM4P2 concrete exhibits almost the equivalent pore structure parameters with the CT0 one at various hydration time. Moreover, CSM4P4 concrete presents a much finer and denser pore structure than the CSP4 one. The results seem to illustrate that the pore-coarsening effect of PVA fibers was partially counteracted by the pore-refinement effect of MgO.

3.5. D_s Analysis

 D_s values of hydraulic concretes containing MgO and/or PVA fiber hydrated at 3, 28 and 180 days are calculated using the MIP results and Equation (2), and the results are shown in Table 8. The correlation coefficients (R^2) of the fitting line in Equation (2) were also exhibited in Table 8. The high R^2 values close to 1.0 in Table 8 demonstrate that the calculated D_s values have high accuracy and reliability. Based on the fractal theory [34,61], if the object has a smooth surface, its D_s is 2.0; if the pore surface of the object is rougher and more complex, its D_s approaches 3.0. Hence, D_s is meaningful only in the range 2.0–3.0. Table 8 exhibits that the D_s values in this study are between 2.576 and 2.979, suggesting that the hydraulic concretes containing MgO and/or PVA fiber possess obvious fractal features.

Table 8 also shows that the D_s values raised with the hydration time, indicating the pores in concrete became rougher and more complex during the hydration process. Moreover, it can be found from Table 8, the addition of MgO increased the D_s values at various hydration ages, and the high MgO dosage would further increase the D_s values, suggesting that the MgO addition obviously made the pore structures of concrete rougher. This finding is consistent with the results in the studies in which mineral materials were adopted in cement-based materials. In those studies, the inclusion of mineral materials such as silica fume, fly ash and granulated blast furnace slag (GBFS) significantly raised the D_s values, because these materials inevitably made the pore structures more complex [34,35,61]. In addition, it can be found from Table 8 that the PVA fiber inclusion reduced the D_s values. This can be expected because the PVA fiber increased the fraction of large pores, as revealed by the MIP results. A larger number of large pores in concrete means there are much more smooth pore surfaces, which results in a relatively lower D_s value.

Notation	Curing Time (days)	Ds	\mathbf{R}^2
	3	2.687	0.956
CT0	28	2.869	0.965
	180	2.931	0.989
	3	2.725	0.968
CSM4	28	2.896	0.963
	180	2.946	0.976
	3	2.776	0.958
CSM8	28	2.915	0.984
	180	2.979	0.963
	3	2.613	0.949
CSP2	28	2.796	0.963
	180	2.896	0.982
	3	2.576	0.976
CSP4	28	2.744	0.981
	180	2.843	0.963
	3	2.665	0.958
CSM4P2	28	2.816	0.967
	180	2.918	0.969
	3	2.601	0.982
CSM4P4	28	2.803	0.991
	180	2.911	0.978

Table 8. Pore surface fractal dimensions of hydraulic concretes containing MgO and/or PVA fiber.

Additionally, the correlation of D_s with the pore structure parameters such as the critical pore diameter, porosity and $V_{50 \text{ nm}-10 \mu\text{m}}$, are presented in Figure 8. From Figure 8, it can be found that the critical pore diameter, porosity and $V_{50 \text{ nm}-10 \mu\text{m}}$ are negatively correlated with D_s , with large R^2 values of 0.973, 0.916 and 0.917, respectively, suggesting the D_s can reflect and characterize the pore structure of hydraulic concretes. As demonstrated by other fractal studies [34,35,61], the D_s can comprehensively and accurately reflect and evaluate the pore structures of concrete.



Figure 8. The correlation between D_s and (a) the critical pore diameter, (b) porosity and (c) $V_{50 \text{ nm}-10 \mu m}$ of concrete.

3.6. Pore Structural and Fractal Analysis

3.6.1. Pore Structural Analysis of the Relationship between the Compressive Strength, Abrasion Resistance and Pore Structures of Concrete

In this study, the relationships between the compressive strength, abrasion resistance and pore structures of hydraulic concretes were investigated. Figure 9 displays the correlations between the compressive strength and pore parameters (porosity and $V_{50 \text{ nm}-10 \text{ }\mu\text{m}}$) of hydraulic concretes. Figure 10 displays the correlation between the abrasion resistance and pore structure parameters (porosity and $V_{50 \text{ nm}-10 \text{ }\mu\text{m}}$) of hydraulic concretes.



Figure 9. The relationship between the compressive strength and (**a**) porosity and (**b**) $V_{50 \text{ nm}-10 \mu \text{m}}$ of hydraulic concretes containing MgO and/or PVA fiber.

Overall, Figure 9 displays that the compressive strengths of the seven concretes in this study reduced as the porosity or $V_{50 \text{ nm}-10 \text{ }\mu\text{m}}$ raised. This is because that, as the hydration time increased, the pore structure was refined and the concrete mechanical property was enhanced. This general trend is consistent with the results reported by others [62], who found that compressive strengths of concretes weakened linearly as the porosity increased. However, the compressive strengths and pore structure parameters of hydraulic concretes containing MgO and/or PVA fiber did not obey a clear and single function, the data are somewhat scattered in Figure 9. In other words, some concretes with relative strong compressive strength in this study did not have the low porosity and low $V_{50 nm-10 \mu m}$ values, and vice versa. Specifically, the PVA fiber addition could slightly raise the porosity and $V_{50 nm-10 \mu m}$ values, as revealed in Section 3.4, but the CSP2 and CSP4 concretes exhibit larger compressive strengths than other concrete mixtures in this study. On the contrary, the inclusion of MgO reduced the porosity and $V_{50 nm-10 \mu m}$ values of CT0 concrete at various hydration age by filling up the large pores, whereas the CSM4 and CSM8 concretes present smaller compressive strengths than the CT0 one. This is due to the fact that, although the Mg(OH)₂ crystals (brucite) produced by the MgO reaction could fill up the pores, they cannot improve the concrete strength since they do not have any bonding property.

Figure 10 exhibits a similar trend with Figure 9. Generally, the abrasion resistance of hydraulic concretes added with MgO and/or PVA fiber reduced as the porosity or $V_{50 \text{ nm}-10 \mu m}$ increased, but the data in Figure 10 did not strictly follow a definite function. This experimental phenomenon can be also explained by the following reason: the Mg(OH)₂ formation could refine the pores but could not enhance the abrasion resistance, while the PVA fiber incorporation marginally increased the porosity and fraction of large capillary pores but it indeed improved the abrasion resistance through the friction effect, crack arresting effect as well as the bridge effect of fibers.





Figure 10. The relationship between the abrasion resistance and (**a**) porosity and (**b**) $V_{50 \text{ nm}-10 \mu \text{m}}$ of hydraulic concretes containing MgO and/or PVA fiber.

3.6.2. Fractal Analysis of the Relationship between the Compressive Strength, Abrasion Resistance and $D_{\rm s}$ of Concrete

The correlations between the compressive strength, abrasion resistance and D_s of hydraulic concretes added with MgO and/or PVA fiber were plotted in Figure 11.



Figure 11. The relationships between the D_s and (a) compressive strength and (b) abrasion resistance of hydraulic concretes containing MgO and/or PVA fiber.

Figure 11 indicates a general trend that the compressive strength and the abrasion resistance of hydraulic concretes increase with D_s values. Nevertheless, Figure 11 shows there are no definite correlation between the compressive strength or abrasion resistance and D_s , since the data are scattered and do not obey any clear function. This implies that, the compressive strength and the abrasion resistance of hydraulic concretes containing MgO and/or PVA fiber are not so closely related with the D_s values.

This finding appears to be in contradiction with previously reported results that there exists a positive relationship between Ds and compressive strength of cement-based materials. For example, Jin et al. [35] found that the compressive strength of mortars added with silica fume increased with the increase in D_s. Similarly, Kim et al. [63] reported that the compressive strengths of cement pastes containing GBFS were linearly correlated with the D_s values. These contradictory findings are probably because that MgO and PVA fiber have quite different effects on the development of compressive strength and D_s with silica fume and GBFS. To be specific, from Jin et al.'s [35] and Kim et al.'s [63] studies, silica fume and GBFS can increase the compressive strength and D_s, thus the compressive strength and

 D_s followed a linear correlation. In this study, the MgO addition could also increase the D_s values, as discussed above, but it weakened the compressive strength. Similarly, the PVA inclusion reduced the D_s values but improved the compressive strengths. Thus, no definite relationship exists between the compressive strength, abrasion resistance and D_s of hydraulic concretes containing MgO and/or PVA fiber in this study.

4. Conclusions

The following conclusions can be obtained.

(1) The incorporation of 4–8% Type I MgO reduced the compressive strength and splitting tensile strength of concrete by about 4.9–15.2%, lowered the abrasion resistance by about 5.4–12.5% at 3, 28 and 180 days, but clearly improved the cracking resistance to dry shrinkage and thermal stresses. It delayed the initial cracking time of concrete rings by 6.5–11.4 h, increased the maximum compressive stress $\sigma_{c,max}$ of concretes by about 15–31%, enhanced the cracking tensile stress σ by about 6–11% and reduced the cracking temperature T_c by about 2.3–4.5 °C.

(2) The inclusion of 1.2–2.4 kg/m³ PVA fibers raised the splitting tensile strength of concrete by about 8.5–15.7% at 3, 28 and 180 days, and slightly enhanced the compressive strength and abrasion resistance of concrete by about 2.2–7.5%. Adding 1.2–2.4 kg/m³ PVA fibers was more efficient than adding 4–8% MgO in enhancing the abrasion resistance and in reducing the cracking risk when subjected to restrained drying and temperature decline.

(3) The concrete with the addition of 4% MgO and 1.2–2.4 kg/m³ PVA fibers presented slightly larger splitting tensile strength than the control concrete. They also exhibited better cracking resistance than the MgO concrete as well as the PVA fiber concrete. The utilization of high dosage of Type I MgO below 8% and PVA fiber no more than 2.4 kg/m³ together is a practical technique to enhance the cracking resistance of hydraulic mass concretes to shrinkage and temperature decline. The excellent cracking resistance of concrete added with MgO and PVA fiber is beneficial for the overall abrasion resistance of hydraulic mass concrete structures that are easy to crack in practice.

(4) The inclusion of MgO refined the pores, whereas the PVA fiber addition slightly coarsened the pore structures of concrete at various hydration ages. The hydraulic concretes incorporated with MgO and/or PVA fiber exhibited obvious fractal features. The compressive strength and the abrasion resistance of hydraulic concretes incorporated with MgO and/or PVA fiber and definite correlation with the pore structure parameters as well as the pore surface fractal dimensions.

5. Future Perspective

The W/B ratio of 0.33 was used in this study. The influences of MgO and PVA fiber on abrasion and cracking resistance, pore structure and fractal features of hydraulic concrete with more W/B ratios will be studied in our future work.

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