



Article The Counterbalance of the Adverse Effect of Abrasion on the Properties of Concrete Incorporating Nano-SiO₂ and Polypropylene Fiber Based on Pore Structure Fractal Characteristics

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Abstract: Abrasion damage is a typical hydraulic structure failure and considerably impacts the durability of buildings. In severe circumstances, it can even prevent hydraulic structures from being used and operated normally. Thus, it is essential to research abrasion-resistant hydraulic systems that are more durable, inexpensive, safe, and ecologically friendly, given its unavoidable characteristics. In this context, five dosages of nano-SiO₂ and three dosages of fibers are selected to evaluate and analyze the modification effect of nano-SiO₂ and polypropylene fibers on the abrasion resistance of concrete. The evolution of the concrete properties was characterized based on the abrasion resistance strength. Moreover, the mineralogical composition and microstructure characterization were investigated through X-ray diffraction and scanning probe microscope. Mercury intrusion porosimetry was applied to determine the pore-structure parameters of concrete, such as pore-size distribution and the fractal characteristics. The results indicate that nano-SiO₂ improves the abrasion resistance of concrete by densifying the pore structure and promoting the formation of hydration products. Results reveal that the excessive dosage of fibers agglomerates in the concrete to form an unsubstantial pore structure due to poor dispersibility. The fractal dimension of the pore structure exhibits a close relationship with the abrasion resistance strength of concrete. The implications of these findings inform the design of abrasion and erosion resistance for hydraulic engineering structures.

Keywords: abrasion resistance; SiO₂ nanoparticles; polypropylene fibers; concrete; fractal dimension

1. Introduction

The abrasion damage of hydraulic concrete is caused by the continuous friction and impact of the sediment, gravel, sand, ice, and other debris mixed in seawater or river water on the concrete surface [1]. In actual engineering, spillway skirts, scuppers, stilling pools, culverts, and bridge abutments are easily damaged by erosion and erosion, resulting in the wear, cracking, and shedding of hydraulic concrete surfaces and even corrosion of steel bars.

Incorporating different materials to improve the abrasion resistance of concrete is the most effective and widely used method in engineering [2–6]. Combined with the form and process of concrete being damaged by abrasion, the materials currently used are mainly through the following three ways: (1) Improve the strength of concrete cement paddle by adding mineral admixtures to form a harder cement shell to resist the damage of high-speed sand-containing water flow, such as silica fume concrete, high-strength concrete, HF concrete, and a series of concrete materials [7]. These concrete materials often have a considerable increase in compressive strength while the abrasion resistance is improved as well. (2) By controlling the cracks generated by the concrete under the action of high-speed sand-containing water flow, the development of cracks is inhibited, the integrity of the



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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/). concrete is improved, and the falling-off of the broken cement stone is delayed, thereby improving the abrasion resistance of the concrete. The influence of this type of material on the compressive strength of concrete mainly depends on the strength of the material itself, but it has a significant improvement in the impact resistance of concrete, such as fiber concrete, epoxy resin concrete, etc. (3) Concrete is prepared by using more hard- and wear-resistant concrete aggregates, such as some special aggregates such as hard iron ore [8]. However, this method cannot be widely promoted in engineering due to the limitation of aggregate origin. According to the application results of various materials mixed into concrete in actual engineering, these methods can improve the impact and wear resistance of concrete, but there are also different use defects and insufficient performance problems.

The main damage pattern of concrete after abrasion damage is cracking [9]. It is very effective to improve the strength level of concrete to achieve a better anti-abrasion effect. However, for the concrete material itself, with the increase of its compressive strength, its crack resistance, ability to resist deformation, and its own brittleness become more prominent. At this time, it is particularly important to control these defects of concrete. The addition of fiber has a very obvious improvement effect on many defects of concrete itself, such as high brittleness and easy cracking [10,11]. Therefore, adding fibers to solve these problems and make concrete more tough and deformable are the main reasons why scholars are keen to evaluate the application of fibers in concrete. By inhibiting the stress shrinkage, temperature, or dry shrinkage of concrete during the hydration process, the development of cracks is delayed, and the expand of internal cracks inside concrete is constrained as well. Polypropylene fiber has the advantages of light weight, high toughness, low price, and chemical resistance and has been widely used in cement-based composite materials in recent years. At the same time, polypropylene fibers can effectively inhibit the growth and development of internal cracks in the early stage of concrete, thereby enhancing the tensile strength and plasticity of concrete.

With the development of nanotechnology, the research on the application of nanomaterials in concrete has become more and more extensive. Compared with silica fume, nano-SiO₂ has a higher specific surface area, so the improvement effect on the interface transition zone (ITZ) is also more prominent [12]. Combined with the unique nucleation effect of nano-SiO₂, it has a significant optimization effect on the internal microscopic defects of concrete. However, the content of nano-SiO₂ is not linearly related to the improvement effect of concrete [13–15]. Since the slump of concrete will also decrease significantly after adding nano-SiO₂, combined with the characteristics that nano-SiO₂ particles are not easy to disperse inside the concrete and considering the inconsistency between test conditions and materials, the current recommendations for the optimal dosage of nano-SiO₂ are also inconsistent to a certain extent [16,17], so the research on the optimal dosage in concrete remains limited.

This study attempts to clarify the combined influence of the nano-SiO₂ and polypropylene fibers on the performance of concrete subjected to abrasion. Our primary aim is to find a proper dosage of nano-SiO₂ and polypropylene fibers to enhance the actual anti-abrasion resistance of concrete. In this context, five dosages of nano-SiO₂ and three dosages of fibers were selected to evaluate and analyze the modification effect of nano-SiO₂ and polypropylene fibers on the abrasion resistance of concrete. The evolution of the concrete properties was characterized based on the abrasion resistance strength. Moreover, the mineralogical composition and microstructure characterization were investigated through X-ray diffraction (XRD) and scanning probe microscope (SEM). Mercury intrusion porosimetry (MIP) was applied to determine the pore-structure parameters of concrete, such as pore-size distribution (PSD) and fractal characteristics. The findings are expected to help design alternative strategies for the durability design of concrete structures against abrasion damage.

2.1. Materials, Casting, and Curing

Ordinary Portland cement (P.O.42.5) and fly ash (20% replacement) were used in this study. Local river sand was used as the fine aggregate with a fineness modulus of about 2.87, and the coarse aggregate was basalt with a diameter of 5–20 mm. The physical performance indicators of various admixtures are shown in Tables 1 and 2. The compositions of the concrete mixtures are listed in Table 3.

Table 1. The chemical composition and loss on ignition of the binding materials.

Binder		Loss on Ignition (%)								
	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	Na ₂ O	K ₂ O	Cl ⁻	LUSS OIL Ignition (76)
Cement	41.27	31.34 58	12.34	3.33	3.34	3.22	0.43	0.80	-	1.09
FIY ash	1.5	58	30	4.5	2.0	1.22	-	1.50	-	0.82

Table 2. Properties of polypropylene fiber.

Fiber	Diameter	Length	Tensile Strength	Elongation	Elasticity	Melting	Specific Gravity
Content (%)	(µm)	(mm)	(MPa)	Ultimate (%)	Modulus (MPa)	Point (°C)	(g/cm ³)
100	20	9	579	27.6	5274	161	1.36

Table 3. Mix proportion of concrete (kg/m^3) .

Code	Water	Cement	Sand	Aggregate	Fly Ash	Nano SiO ₂	Polypropylene Fiber	Superplasticizer
NC	165	330	674.1	1198.4	82.5	0	0	0.8%
PFC	165	330	674.1	1198.4	82.5	0	0.9	0.85%
PF-NS1	165	325.875	674.1	1198.4	82.5	4.125	0.9	0.95%
PF-NS3	165	317.625	674.1	1198.4	82.5	12.375	0.9	1.25%
PF-NS5	165	309.375	674.1	1198.4	82.5	20.625	0.9	1.65%
PF-NS7	165	301.125	674.1	1198.4	82.5	28.875	0.9	1.9%
PF6-NS3	165	317.625	674.1	1198.4	82.5	12.375	0.6	1.25%
PF12-NS3	165	317.625	674.1	1198.4	82.5	12.375	1.2	1.25%
L-PF-NS3	150	317.625	674.1	1198.4	82.5	12.375	0.9	1.35%
H-PF-NS3	180	317.625	674.1	1198.4	82.5	12.375	0.9	1%

First, nano-SiO₂ and polycarboxylate superplasticizer were added into an aqueous solution and stirred for two minutes to make a uniformly dispersed nano-SiO₂ solution. Next, coarse aggregate, cement, fly ash, and fine aggregate were added into the mixer for two minutes. Then, the remaining water and nano-SiO₂ solution were added to the mixer and mixed for two minutes. Finally, polypropylene fibers were added and stirred for another two minutes to prepare a paddle with good fluidity. After vibrating the concrete mixture loaded into the concrete mold on the vibrating table, it was left to stand for 24 h and then demolded.

All specimens were prepared; refer to Specifications for the mix proportion design of ordinary concrete (JGJ55-2011) and cured at 20 ± 2 °C and 95% RH until an age of 28 days [18], as shown in Figure 1.



Figure 1. Concrete curing process.

2.2. Experiment Methods

2.2.1. Abrasion Resistance Strength

The concrete abrasion test was carried out by using the HKCS-2 testing machine designed in DL/T5332-2005 [19]. The high-speed centrifugal force was used to rotate the impeller to make the sand-containing water flow impact the inner ring of the concrete to determine the ability of the concrete surface to resist the impact and wear damage of the high-speed, sand-containing water flow after 28 and 60 days. The test equipment and specimen are shown in Figure 2. Each group consisted of three replicate specimens.



Figure 2. (a) Abrasion tester, and (b) specimen.

The sand content of water flow is 20% by mass. The single flushing time was 30 min, then the abrasive was replaced, and the operation was repeated 4 times. Additionally, when the saturated surface of the specimen was dry, the mass (g) of the specimen was weighed, and the total abrasion resistance of the specimen was calculated by Equation (1):

. .

$$f_a = \frac{tA}{\Delta M} \tag{1}$$

where f_a (h/(kg/m²)) is the abrasion resistance strength, *t* (h) is the cumulative abrasion time of specimens, *A* (m²) is the scour area the specimen, and ΔM is the accumulated mass change of the specimen.

2.2.2. Microstructural Monitoring

The mineral phases, morphology, and pore structure of the concrete samples were characterized to assess the alterations caused by the abrasion damage process. Utilizing a Bruker diffractometer with a copper target operating at 45 kV and 40 mA, we qualitatively analyzed the amorphous substances in the altered sample. The XRD patterns were recorded in a 2θ angle range of 5°–50° with a counting time of 50 s/step and a step size of 0.016°. MIP at a contact angle of 130° and surface tension of 485 dynes/cm (Hg) evaluated the PSD of the mortars; additionally, the fractal dimension of the specimen was calculated according to the results of PSD. SEM was performed on a Zeiss Sigma 500 microscope to identify the morphology and microstructure of the samples on a microscale. Electron probe microanalysis (8050G, EPMA) was used to characterize and image the demineralization process and its consequence on matrices in the mortar samples after abrasion damage.

2.2.3. Fractal Dimension

Fractal geometry can be used to quantitatively characterize the irregularity, disorder, and complexity of shapes [20,21]. The pore network of eroded concrete exhibits significant fractal geometrical characteristics. The fractal modeling of porous materials is based on the principle of the Menger sponge (Karl and Menger, 1935). A cube with a side length R is divided into m^3 equal cubes, some small cubes are removed according to a rule, and the remaining small cubes have a length N_1 (m). This process is carried out iteratively. Hence, the number of remaining cubes continues to increase, while the sizes of the cubes continue to decrease. The remaining infinite number of small cubes constitute the matrix of the material, and the removed small cubic spaces of different orders make up the pore grid of the material. After performing the removal process by k times, the remaining cube size is $r_k = R/m_k$, and its number can be calculated using Equation (2):

$$N_k = N_1^k = (r_k / R)^{-D}$$
(2)

where D is the volume fractal dimension of the geometry. D is obtained using Equation (3).

$$D = \log(N_1) / \log(m) \tag{3}$$

The volume of the solid structure is then calculated using Equation (4).

$$V_k \sim r_k^{3-D} \tag{4}$$

When $K \to \infty$ or $r_k \to 0$, $V_k \to V(r)$, and we can obtain Equation (5).

$$dV_k/dr_k \sim r_k^{2-D} \tag{5}$$

According to the pore volume of the concrete $V_p(r) = R^3 - V(r)$, we obtain Equation (6):

$$\log\left[-dV_p/dr\right] \sim (2-D)\log r \tag{6}$$

where V_p is the cumulative invasion volume of mercury under pressure *P*, *r* is the pore radius of the concrete specimen, and *D* is the fractal dimension.

The pore volume of concrete was measured using the MIP method, and the fundamental principle was expressed using the Washburn equation and calculated using Equation (7):

$$p = \frac{2T\cos\theta}{r} \tag{7}$$

where *T* is the surface tension of mercury, θ is the contact angle between mercury and the solid, and *P* is the pressure exerted when mercury invades.

Equations (6) and (7) were used to establish the relational expression of the fractal dimension, as expressed in Equation (8).

$$\log\left[-dV_p/dr\right] \sim (D-4)\log(P) \tag{8}$$

3. Results and Discussion

3.1. Abrasion Resistance Strength

Figure 3 shows the change in the abrasion resistance strength of modified concrete. Table 4 lists the abrasion resistance strength of the selected sample. Compared with the PFC and NC specimens, it is found that the incorporation of polypropylene fibers can effectively enhance the abrasion resistance of concrete, and the abrasion rates of concrete after curing for 28 days and 60 days are reduced by 3.04% and 2.17%, respectively, compared with ordinary concrete. This is mainly due to the fact that the surface cement slurry is washed and worn away in the process of concrete being eroded and damaged by high-speed water flow, and the polypropylene fibers will form an overlapping network structure inside the concrete, which will have a restraining effect on the aggregates in the concrete. Additionally, for the broken cement block, the bond between the polypropylene fiber and it can also keep it on the concrete, continuing to resist the impact of high-speed sand-containing water flow abrasion damage, and the corresponding concrete abrasion resistance is also improved. When the content of polypropylene fiber is 1.2 Kg/m^3 , it cannot be well-dispersed in the concrete, and the agglomeration of the fiber causes it to become a weak area inside the concrete, which has a negative impact on the formation of the dense structure inside the concrete. Nevertheless, the restraining effect of fibers on the block damaged by impact wear and the reinforcing effect of nanoparticles on the cement matrix still make the abrasion resistance strength of the PF12-NS3 samples enhanced. Comparing the abrasion resistance strength of 28 days and 60 days, it can be found that the addition of excess fiber has a great influence on the formation of the compact structure inside the concrete.

Code	Curing for 28 Days	Curing for 60 Days
NC	0.1	0.117
PFC	0.141	0.154
PF-NS1	0.325	0.304
PF-NS3	0.315	0.36
PF-NS5	0.364	0.334
PF-NS7	0.094	0.094
PF6-NS3	0.173	0.203
PF12-NS3	0.182	0.188
L-PF-NS3	0.223	0.232
H-PF-NS3	0.14	0.153

Table 4. Abrasion resistance strength of selected sample.

Overall, the addition of nano-SiO₂ could enhance the abrasion resistance of concrete. When the nano-SiO₂ content was 5%, the concrete had the highest abrasion resistance strength. However, when the content of nano-SiO₂ was increased to 7%, with too much nano-materials agglomerate in the concrete, the wrapped water molecules hindered the hydration of the cement so that the fibers were not firmly bonded to the matrix in the concrete, and the internal structure of the concrete was weakened. Consequently, the abrasion resistance strength of concrete was reduced.



Figure 3. Change in concrete's abrasion resistance strength at different proportions after curing for (**a**) 28 days and (**b**) 60 days.

3.2. Mineral Phases by XRD

Figure 4 illustrates XRD spectrum of the nano-SiO₂ and polypropylene fiber modified concrete with different dosages when the curing age was 28 days. With the increase of curing age, the characteristic peak value of C_3S in concrete decreased more obviously, indicating that most of the cement had been hydrated into C-S-H gel, and the addition of nano-SiO₂ will make the content of C_3S decrease heavily, indicating the greater degree of cement hydration. At the same time, the change of fiber content also affected the change of C_3S content in concrete. Comparing several groups of ratios of fiber content change, when the content was 0.9 kg/m³, it had the best effect of promoting hydration.

The addition of nano-SiO₂ increased the content of $Ca(OH)_2$ in the concrete, but then its characteristic peak had a significant decrease. It shows that in the early stage of curing, the addition of nano-SiO₂ into the concrete will promote the hydration of the cement, and the amount of generated $Ca(OH)_2$ will be enhanced. Subsequently, due to the small specific surface area and high chemical activity of nano-SiO₂, the hydration of $Ca(OH)_2$ is further promoted to form C-S-H gel. When curing for 28 days, the amount of $Ca(OH)_2$ crystals in the concrete was the least when the content of nano-SiO₂ was 3%, which is consistent with the strength change exhibited by the macroscopic mechanical properties. When the nano-SiO₂ content reached 7%, it can be seen that the effect of nano-SiO₂ on the further hydration of the generated $Ca(OH)_2$ crystals was small, and the quantity of C-S-H gels generated in the concrete as also hard to notice. At the same time, it is obvious that the change in fiber content has little effect on the amount of Ca(OH)₂ crystals, but the change in water consumption has a greater effect on the promotion of hydration by nano-SiO₂. The results indicate that lower water consumption inhibits further hydration of concrete in the later stages of curing.



Figure 4. XRD patterns of concrete with different dosages of nano-SiO₂ and polypropylene fiber. (a) varied dosage of nano-SiO₂, (b) varied dosage of polypropylene fiber, (c) varied dosage of water, (d) varied curing time.

3.3. Pore Structure Fractal Characteristic by SEM and EPMA

In order to further understand the effect of nano-SiO₂ and polypropylene fibermodified concrete on its properties and abrasion resistance, the concrete samples under proportions were observed by SEM technology. Overall, the incorporation of nano-SiO₂ made the internal microstructure of concrete more compact. As shown in Figure 5c–f, the content of calcium hydroxide crystals inside the nano-SiO₂ modified concrete decreased greatly, and only a small amount of exposed ettringite was found in the C-S-H gel stacking structure. At this time, the C-S-H gel in the concrete had formed a relatively dense structure under the early hydration of nano-SiO₂.



(j)

Figure 5. SEM results of concrete with different dosages of nano-SiO₂ and polypropylene fiber after 28 days curing. (a) NC, (b) PFC, (c) PF-NS1, (d) PF-NS3, (e) PF-NS5, (f) PF-NS7, (g) PF6-NS3, (h) PF12-NS3, (i) L-PF-NS3, and (j) H-PF-NS3.

When the curing age continued to increase to 28 d, the larger content of C-S-H gel completely wrapped the network fiber structure, and the structures were stacked in an orderly manner, forming a continuous structure with high uniformity. Additionally, its internal Ca(OH)₂ and AFt crystals were mostly hydrated into C-S-H gels under the promotion of nano-SiO₂. Moreover, part of the fly ash's surface-active substances was also consumed by hydration, exposing iron oxides within it that cannot be hydrated. When the content of nano-SiO₂ was 3%, the microstructure of the sample was the densest. Combined with the effect of polypropylene fibers, the microstructure of the C-S-H gel was optimized. The denser polypropylene fiber network structure makes the packing morphology of C-S-H gel more compact. At the same time, needle-like AFt crystals can also fill the pores in the middle of the network structure and hydrate to form C-S-H gel under the promotion of nano-SiO₂, which ensures its stability and further compacts the microstructure of concrete. When the dosage was 5%, although there exists a small part of nano-SiO₂ particles that was not well dispersed, it did not become a weak area inside the concrete; consequently, the strength of the concrete was promoted as well.

The growth space of calcium hydroxide crystals in concrete will be compressed with the increase of nano-SiO₂ content, which will make the hardened cement structure loose and reduce the impact and wear resistance of concrete. As is shown in Figure 5f, due to the high water absorption of nanoparticles, at the same age, the distribution of calcium silicate hydrate inside the concrete was less, and the contents of AFt and Ca(OH)₂ increased. The microstructure of PF-NS7 concrete is mainly composed of needle-like and flake-like crystals and agglomerated nanoparticles, and the consistency and continuity of the structure are poor, which corresponds to the poor macroscopic mechanical properties of concrete mixed with 7% nano-SiO₂.

In the ratio of changing the content of fibers by fixing the content of nano-SiO₂, the microstructure of concrete formed by the change of fibers was also different. When the fiber content was 0.6 kg/m^3 , the lap joint of the fibers in the concrete was relatively discontinuous, and the hydration products in the concrete had obvious regional distribution characteristics, resulting in poor continuity of the concrete microstructure and the accumulation of C-S-H gel, which makes its internal microscopic appearance uneven. It is worth noting that the uneven surface accelerates the cavitation damage of high-speed water flow during the abrasion process.

Figure 6 illustrates BSE image associated with O, Al, Si, S, and Ca mappings of the PF-NS3 and PF-NS5 sample after abrasion damage. The lap joint of the fibers inside the damaged concrete is discontinuous, and the hydration products inside the concrete show the characteristics of regional distribution, resulting in poor continuity of the concrete microstructure After the abrasion damage, a large number of micro-cracks appeared inside the concrete. These micro-cracks expanded each other and became weak areas of concrete deterioration. The microstructure of concrete with a nano-SiO₂ content of 3% was the densest. Under the synergistic toughening of polypropylene fibers, the abrasion resistance of C-S-H gel increased to a certain extent. This is because that the network structure formed by polypropylene fibers makes the packing of C-S-H gel denser, and at the same time, nano-SiO₂ can be filled between the network structures formed by AFt crystals, thereby promoting the formation of C-S-H gel by hydration. The synergistic effect of the two substances increased the degree of the compaction of the concrete matrix while maintaining the structural stability.

3.4. Pore Size Distribution by MIP

Figure 7 depicts the PSD of selected sample on the basis of five predefined pore ranges. Concrete pore-size distribution is separated into five categories: "harmless pores" ($d \le 20 \text{ nm}$), "less harmful pores" ($20 \text{ nm} \le d \le 50 \text{ nm}$), "harmful pores" ($50 \text{ nm} \le d \le 200 \text{ nm}$), and "more harmful pores" (d > 200 nm) [11]. As shown in the figure, with the increase of nano-silica, the proportion of harmless pores and less harmful pores in concrete increases, and the proportion of harmful pores and porous pores decreases. Apparently, this is due to the self-filling effect of nano-SiO₂ and its promotion in the cement hydration process. The observations derived herein are in agreement with those presented in ref. [22]. Moreover, the increase in fiber dosage caused the opposite effect. Poor dispersibility leads to the agglomeration of a large amount of fiber inside the concrete pores, increasing the proportion of macropores in the concrete (see Figures 5 and 6).



(**b**)

Figure 6. BSE image associated with O, Al, Si, S, and Ca mappings of the PF-NS3 and PF-NS5 sample after abrasion. (**a**) PF-NS3 sample, (**b**) PF-NS5 sample.



Figure 7. Pore-size distribution of selected sample with different dosages of (a) nano-SiO₂ and (b) polypropylene fiber.

3.5. Fractal Analysis

Table 5 shows the fractal dimension of the selected sample. As shown in the table, the addition of nano-SiO₂ increases the fractal dimension of concrete. This indicates that nano-SiO₂ optimizes the pore size distribution in concrete, changes the macroporous structure into small pores, and increases the complexity of the internal pore structure of concrete [23]. This is due to the micro-aggregate filling effect of nano-SiO₂. When the content of nano-SiO₂ increases to 7%, the fractal dimension of concrete begins to decrease, and the proportion of harmless pores and harmful pores also decreases. Firstly, when the dosage of nano-SiO₂ is too high (7%), too much nano-materials agglomerate in the concrete, and the wrapped water molecules hinder the hydration of the cement so that the fibers are not firmly bonded to the matrix in the concrete, and the internal structure of the concrete is weakened. Secondly, under the synergistic effect of nano-SiO₂ dosage is relatively high, and the complexity of pores is relatively low, so its fractal dimension is relatively low compared with specimen incorporating 3% nano-SiO₂.

Table 5. Fractal dimension of selected sample.

Code	Nano-SiO ₂ Content (%)	Polypropylene Fiber (kg/m ³)	Ds	R ²
NC	0	0	2.6	0.997
PFC	0	0.9	2.83	0.998
PF-NS1	1	0.9	2.920	0.996
PF-NS3	3	0.9	2.813	0.997
PF-NS5	5	0.9	2.965	0.997
PF-NS7	7	0.9	2.73	0.994
PF6-NS3	3	0.6	2.88	0.998
PF12-NS3	3	1.2	2.86	0.996
L-PF-NS3	3	0.9	2.91	0.997
H-PF-NS3	3	0.9	2.80	0.998

The abrasion resistance of concrete is closely related to the internal pore structure. Figure 8 shows the relationship between the fractal dimension of concrete and the abrasion resistance strength. It can be seen from the fitting results in Figure 8 that the fractal dimension is linearly correlated with the abrasion resistance strength, and the correlation coefficient is high. The greater the fractal dimension of concrete, the greater the abrasion resistance under high-speed flow scouring and the better the toughness. PF-NS5 concrete has the highest fractal dimension [24], so its anti-abrasion performance is the highest.



Figure 8. Relationship between fractal dimension and abrasion resistance strength of the selected sample.

4. Conclusions

By experimentally determining the abrasion resistance strength, mineral phases alterations, morphology, and pore structure and calculating the fractal dimension of different dosages of nano-SiO₂ and polypropylene fiber, our results elucidate the mechanism for synergistic effect of nano-SiO₂ and polypropylene fiber on the properties of concrete. The observations derived here might may help steer the definition of more appropriate recommendations in actual engineering. From the macroscopic and microscopic results discussed above, the following conclusions can be drawn:

- (1) When the dosage is between 1% and 5%, nano-SiO₂ can compact the microstructure of concrete and promote the hydration of cement to generate more Ca(OH)₂ and AFt crystals in the early stage of curing. Due to its small specific surface area and high chemical activity, nano-SiO₂ can continue to play the role of control and refinement during the hydration process, reducing the proportion of macro-pores inside concrete and increasing the formation of C-S-H gel. When the dosage of nano-SiO₂ is 3%, the internal structure of concrete is the optimum. However, excessive dosage will increase the content of harmful pores and inhibit the hydration process of cement.
- (2) When the content of polypropylene fibers is 0.9kg/m³, the fibers form a stable structure, overlapping each other inside the concrete, which promotes a smoother and flatter microstructure of the matrix. At the same time, under this dosage, the fibers can restrain the separation of the broken cement blocks during the process of abrasion damage, thereby improving the abrasion resistance of concrete. However, a too-high fiber dosage, such as 1.2 kg/m³, will produce a vulnerable pore structure due to the unfavorable dispersibility of fibers, resulting in an increase in pore volume and a decrease in concrete performance.
- (3) The internal pore structure of concrete with nano-SiO₂ and polypropylene fiber shows obvious fractal characteristics. At the same time, the fractal dimension has a close positive correlation with the concrete abrasion resistance strength. The larger the fractal dimension, the higher the abrasion resistance strength and toughness of concrete.
- (4) In general, the incorporation of nano-SiO₂ and polypropylene fibers in concrete improves the abrasion resistance of concrete. Nano-SiO₂ can promote cement hydration, compact the microstructure of concrete, and enhance the bond between the cement matrix and the fibers so that the fibers can fully exert the restraint effect on the broken cement blocks. Moreover, the polypropylene fiber in the concrete will also play a role in controlling the cracks that are easily generated in the early stage after the incorporation of nano-SiO₂. The results derived show that when the contents of nano-SiO₂

and polypropylene fiber are 3% and 0.9 kg/m^3 , the effect of improving the abrasion resistance of concrete is the best. In practical engineering, it is recommended to use the mix proportion of the PF-NS3 specimen to improve guidance on the mixture design of concrete when exposure to abrasion is expected in the field.

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