

EXPERIMENTAL STUDY OF THE CHLORIDE-ION PERMEABILITY OF BAMBOO-FIBER-REINFORCED CONCRETE

EKSPERIMENTALNA ŠTUDIJA PERMEABILNOSTI KLORIDNIH IONOV V BETONU OJAČANEM Z BAMBUSOVIMI VLAKNI

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This study investigated the chloride-ion permeability of C30 concrete by adding bamboo fibers with different treatments (untreated, treated with calcium hydroxide solution and treated with sodium hydroxide solution) and different dosages. Three testing methods, namely the electric-flux method, AC test method and the RCM method, were used to characterize the concrete. Parameters such as electric-flux value, AC resistivity and chloride-ion diffusion coefficient were obtained. Results showed that the surface impurities of the bamboo fibers treated with calcium hydroxide solution were removed and the thermal stability of the bamboo fibers was improved, which can effectively enhance the chloride-ion permeability of concrete. Compared to untreated bamboo fibers, the improvement rate was between 14 % and 17 %. Sodium hydroxide is a strong alkaline solution, which can easily disrupt the structure of bamboo fibers and reduce the resistance of concrete to chloride-ion penetration. The best chloride-ion permeability was achieved when the bamboo fiber content reached 2 %. The electric-flux method, AC test method, and the RCM method were mutually validated with good correlation. It is recommended to choose a suitable and simple method for testing. Bamboo-fiber concrete lays a solid foundation for the future transformation of the civil-engineering industry.

Keywords: bamboo fibers, microstructure, AC resistivity, chloride-ion diffusion coefficient

V članku avtorji opisujejo raziskavo permeabilnosti kloridnih ionov v betonu vrste C30, kateremu so dodani različni deleži različno obdelanih bambusovih vlaken (neobdelana vlakna, obdelana v raztopini kalcijevega hidroksida in vlakna obdelana v raztopini natrijevega hidroksida). Karakterizacijo izdelanih betonov so izvedli s tremi različnimi metodami: z metodo električnega fluksa, metodo z izmeničnim električnim tokom in RCM metodo. S pomočjo teh metod so določili vrednosti električnega fluksa, upornost izmeničnega električnega toka in difuzijski koeficient kloridnih ionov. Rezultati preizkusov so pokazali, da so bile z obdelavo v raztopini $\text{Ca}(\text{OH})_2$ odstranjene površinske nečistoče bambusovih vlaken. Izboljšala se je tudi termična stabilnost bambusovih vlaken, kar je učinkovito zmanjšalo tudi permeabilnost kloridnih ionov v betonu. V primerjavi z neobdelanimi bambusovimi vlakni sta se vrednosti izboljšali za 14 % oziroma 17 %. Raztopina natrijevega luga (NaOH) je močna alkalna raztopina, ki z lahkoto poruši strukturo bambusovih vlaken in zmanjša odpornost betona za penetracijo (prodiranje) kloridnih ionov. Najboljšo permeabilnost kloridnih ionov so avtorji dosegli pri dodatku 2 %-ov bambusovih vlaken. Vse tri uporabljene metode preiskovanja so avtorji uspešno medsebojno ovrednotili in nato priporočajo uporabo najprimernejše in najenostavnejše metode. Temelji oziroma podlage iz betonov ojačanih z bambusovimi vlakni so trdna osnova za prihodnjo uveljavitev njihove uporabe v industriji gradbeništva.

Ključne besede: bambusova vlakna, mikrostruktura, upornost izmeničnega toka, difuzijski koeficient kloridnih ionov

1 INTRODUCTION

China, as a developing country, has experienced rapid development in science, technology, and construction, achieving remarkable accomplishments and working towards sustainable development.^{1,2} However, due to limited technological capabilities, there is often a risk of low-quality construction. To expedite construction progress, many organizations incorporate chlorides into concrete, which exacerbates the phenomenon of structural damage. With its vast territory and abundant marine resources, China has developed numerous coastal tourist cities with dense coastal constructions. Chloride ions from the ocean constantly corrode reinforced concrete structures, resulting in extensive damage. Additionally,

in the cold winters of northern China, the durability of bridge roads is compromised due to the use of de-icing salts over an extended period, leading to increased maintenance costs and economic losses.³ Therefore, it is necessary to study the erosion and damage mechanisms of chloride ions and enhance the chloride-ion permeability resistance of hydraulic concrete.

As a natural fiber, bamboo offers the advantages of being environmentally friendly, widely available, and low-cost. Adding bamboo fibers to concrete can reduce its porosity and enhance its resistance to chloride-ion permeability. Currently, there is a lack of research on bamboo-fiber-reinforced concrete regarding the chloride-ion permeability, both domestically and internationally. Scholars have conducted studies on the resistance to chloride-ion permeability by adding other fibers to concrete. Jiang et al.⁴ found that polyvinyl alcohol (PVA) fi-

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bers can improve the resistance to chloride-ion permeability of cement-based composites, but excessive content can have adverse effects. Wang et al.⁵ studied the chloride-ion permeability of polypropylene fiber-reinforced concrete under dry-wet cycle conditions and found that incorporating a volume content of 0.1 % of polypropylene fibers yielded the greatest improvement in the resistance to chloride-ion permeability. Wang⁶ discovered that fibers can enhance the resistance to chloride-ion permeability of concrete, and the better the hydrophilicity of the fiber, the more pronounced the enhancement effect on the resistance to chloride-ion permeability. Liu⁷ found that an appropriate amount of hybrid fibers (volume content of 0.2 % for polypropylene fibers and 0.3 % for basalt fibers) can effectively improve the pore structure of concrete. The longer the curing time of concrete, the more significant the improvement effect on the pore structure. Guo et al.⁸ discovered that the chloride-ion concentration of concrete beams with basalt fibers is lower than that of beams without basalt fibers, with a peak-concentration reduction of approximately 1 %. Zheng et al.⁹ found that incorporating a volume ratio of 1.2 % basalt fibers reduced the electric flux of concrete by 442 C and improved the chloride-ion permeability rating from low to very low. Fan¹⁰ stated that the chloride-ion permeability of basalt-fiber-activated powder concrete can be considered negligible. When the water-binder ratio is 0.22 and the volume content of fibers is 0.10 %, the resistance to chloride-ion permeability of basalt fiber-activated powder concrete is optimized. Kirthika et al.¹¹ found that the chloride-ion permeability rate of ordinary concrete is 49% higher than that of basalt fiber-reinforced concrete. Niu et al.¹² demonstrated that the diffusion coefficient of chloride ions in C30, C40, and C50 concrete decreases by 77.8 % when an appropriate amount of basalt-polypropylene fibers are added, but an excessive fiber content has adverse effects on the resistance to chloride-ion permeability of concrete.^{13–17}

In summary, different fibers can enhance the resistance to chloride-ion permeability of concrete. However, very few studies have been conducted on the durability of bamboo-fiber concrete at home and abroad. Bamboo fibers possess advantages that synthetic fibers like basalt fibers and polypropylene fibers do not have. Bamboo fibers are not only environmentally friendly and beneficial to physical and mental health but also widely available and extremely low-cost. Nanping of Fujian is called the "Hometown of Bamboo" and has a large amount of bamboo fiber. They offer an opportunity to utilize the residual waste from bamboo factories. Bamboo fibers possess advantages that synthetic fibers like basalt fibers and polypropylene fibers do not have. The world is emphasizing sustainable development.^{18,19} Well aligning with this theme, bamboo fibers are not only environmentally friendly and beneficial to physical and mental health but also widely available and extremely low-cost. They offer

an opportunity to utilize the residual waste from bamboo factories. In this paper, flock-like bamboo fibers are first subjected to a microscopic analysis by optical microscope and thermal analysis, analyzing their chemical composition and internal characteristics. Then the bamboo fibers treated with different methods (untreated, treated with calcium hydroxide solution and treated with sodium hydroxide solution), and at different dosages (0, 0.5 %, 1 %, 1.5 %, 2 %, 2.5 %), will be added to C30 concrete for chloride-ion permeability experiments. The effects of the treatment method and dosage of the flock-like bamboo fibers on the resistance to the chloride-ion permeability of concrete will be determined to provide theoretical references and practical evidence for the durability performance of concrete.²⁰

2 RAW MATERIALS AND RESEARCH METHODS

2.1 Raw materials

Bamboo fiber: Utilizing the advantage of "bamboo village" in Nanping City, Fujian Province, China, the waste bamboo fiber from bamboo factories is used, with an average fiber age of approximately 3–4 years, about 4 cm long. Put the bamboo fibers into calcium hydroxide solution and sodium hydroxide solution for 5 min, and then take them out for use. The bamboo fibers were put into calcium hydroxide solution and sodium hydroxide solution for 5 min, which were then taken out for use. Bamboo fibers were put into the drying oven to dry for 24 h, then taken out and spared.

Cement: The volcanic ash-based Portland Pozzolana Cement P.P32.5 is mainly composed of Portland cement clinker, 20–50 % volcanic ash admixture, and gypsum. It has low heat of hydration, good impermeability, and corrosion resistance, poor frost resistance and heat resis-



Figure 1: Flock-like bamboo fiber

tance, high shrinkage, low early strength, and rapid strength development in the later stages.

Crushed stone: In this experiment, crushed stones with a particle size of 5–40 mm are used as coarse aggregates. They are required to have a hard texture, clean and rough surface, and well-graded distribution.

Medium Sand: River sand from Nanping, Fujian province is selected, and its basic theoretical performance parameters are shown in **Table 1**.

Table 1: Basic performance parameters of sand

Type	Clay content (%)	Apparent density (kg/m ³)	Bulk density (kg/m ³)	Void ratio (%)	Fineness modulus
Sand	2.0	2521	1514	39.9	2.4

Calcium hydroxide: Food-grade calcium hydroxide with a purity of 95% in white-powder form is used. An appropriate amount is dissolved in water and stirred to obtain a solution of calcium hydroxide.

Sodium hydroxide: Food-grade calcium hydroxide with a purity of 95% in white powder form is used. An appropriate amount is dissolved in water and stirred to obtain a solution of sodium hydroxide.

2.2 Mix design

According to the "Standard for Basic Performance Test Method of Concrete in Building" (JGJ/T 70-2009),²¹ the consistency of the concrete is controlled at a range from 70 mm to 90 mm, and the apparent density should be greater than or equal to 1900 kg/m³. After trial adjustments, the selected laboratory mix for concrete is shown in **Table 2**.

Table 2: Baseline mix for concrete

Cement (kg/m ³)	Crushed stone (kg/m ³)	Bulk density (kg/m ³)	Water (kg/m ³)
402	1215	598	185

The untreated bamboo fiber, bamboo fiber treated with calcium hydroxide solution and bamboo fiber treated with sodium hydroxide solution were separately added to the concrete at different dosages for experimentation. The specific mix design parameters are shown in **Tables 3 to 5**.

Table 3: Mix parameters for concrete with bamboo fiber untreated

Cement (kg/m ³)	Crushed stone (kg/m ³)	Bulk density (kg/m ³)	Water (kg/m ³)	Untreated bamboo fiber	
				Volume ratio	Dosage (kg/m ³)
402	1215	598	185	0	0
402	1215	598	185	0.5	2.01
402	1215	598	185	1	4.02
402	1215	598	185	1.5	6.03
402	1215	598	185	2	8.04
402	1215	598	185	2.5	10.05

Table 4: Mix parameters for concrete with bamboo fiber treated with calcium hydroxide solution

Cement (kg/m ³)	Crushed stone (kg/m ³)	Bulk density (kg/m ³)	Water (kg/m ³)	Untreated bamboo fiber	
				Volume ratio	Dosage (kg/m ³)
402	1215	598	185	0	0
402	1215	598	185	0.5	2.01
402	1215	598	185	1	4.02
402	1215	598	185	1.5	6.03
402	1215	598	185	2	8.04
402	1215	598	185	2.5	10.05

Table 5: Mix parameters for concrete with bamboo fiber treated with sodium hydroxide solution

Cement (kg/m ³)	Crushed stone (kg/m ³)	Bulk density (kg/m ³)	Water (kg/m ³)	Untreated bamboo fiber	
				Volume ratio	Dosage (kg/m ³)
402	1215	598	185	0	0
402	1215	598	185	0.5	2.01
402	1215	598	185	1	4.02
402	1215	598	185	1.5	6.03
402	1215	598	185	2	8.04
402	1215	598	185	2.5	10.05

2.3 Test method

Optical microscopy analysis: A small amount of sample was adhered to a glass slide and changes in the surface structure of the samples were observed to analyze the similarities and differences.

Thermal analysis: Tests were carried out using a simultaneous thermal analyzer with a nitrogen flow rate of 50 mL/min, a heating rate of 100 °C/min, and a temperature range of 30–1000 °C.

In this study, three methods were used to investigate the chloride-ion permeability of concrete, i.e., the electric-flux method, AC test method, and the RCM method. The research methods are described as follows.

Electric-Flux Method: The resistance to chloride-ion permeability is characterized by electric flux and referenced to the "Standard Test Method for Long-Term Performance and Durability of Ordinary Concrete" (GB/T50082-2009).²² The electric flux test apparatus is shown in **Figure 2**. After curing the cylindrical concrete samples with a diameter of 100 mm and a thickness of 50 mm for a specified time, they are exposed to the air to dry the surface. The side of the specimens is coated with sealing material, then placed in a vacuum container for vacuum saturation. Inside the testing tank, the positive electrode of the specimen is injected with a NaOH solution having a concentration of 0.3 mol/L, and the negative electrode is injected with a 3 % NaCl solution. A DC 60 V is applied axially, and the current passing through the specimen is recorded every 5 min for a duration of 6 h. The total electric flux can be calculated based on the change in current over the 6-hour period.

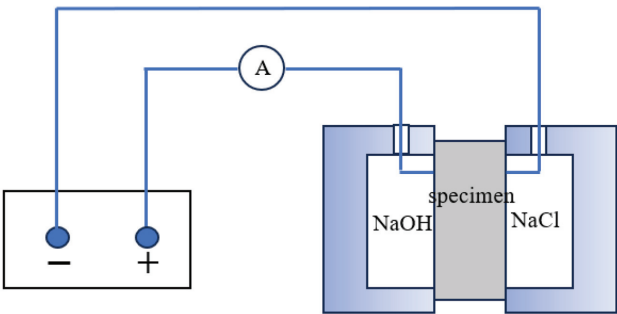


Figure 2: Schematic diagram of the electric flux test device

AC-Current Test Method: The test is carried out according to the relevant specifications, using a concrete resistivity tester and a testing tank (Figure 3). The optimization of the resistivity testing apparatus includes: (i) adopting a new wire connection method, where the connection between the wire and the tester remains the same, and the connection joint with the copper plate uses a pure copper alligator clip directly clamped onto the copper plate, eliminating the use of terminal blocks; (ii) an additional opening for venting is added at the middle of the upper part of the testing tank; (iii) sealing is done using double-sided tape; (iv) a new type of clamping fixture is used. After the specimens are saturated with water under vacuum conditions, their height and diameter are measured with an accuracy of 0.1 mm. Then, the specimen's cylindrical sides are coated with silicone sealing material. Before testing, the specimens are sealed with strong double-sided tape, fixed with the new clamping fixture, and tested according to the aforementioned specifications.

3 RESULTS AND DISCUSSION

3.1 Analysis of the microstructure of bamboo fibers

The enlarged structures of bamboo fibers untreated, treated with calcium hydroxide solution and treated with sodium hydroxide solution are shown in Figure 4:

From Figure 4 it can be observed that the untreated bamboo-fiber surface is covered with a thick adhesive substance, similar to fructose, making it appear relatively heavy. In contrast, the bamboo-fiber surface treated with calcium hydroxide solution no longer shows a thick layer of adhesive substance, and it appears lighter. Furthermore, the internal connecting structure of the bamboo fiber is clearly visible. In the case of THE bamboo fiber treated with sodium hydroxide solution, there is no visible adhering substance on the surface, indicating that the solution has effectively removed impurities from the bamboo-fiber surface. However, the internal connecting structure of the bamboo fiber is not clearly visible, and it appears loose and fragile.

Analysis of the reasons: The bamboo-fiber surface contains various impurities, such as sugars and pectin.²³ THE Calcium hydroxide solution is a weak alkaline so-

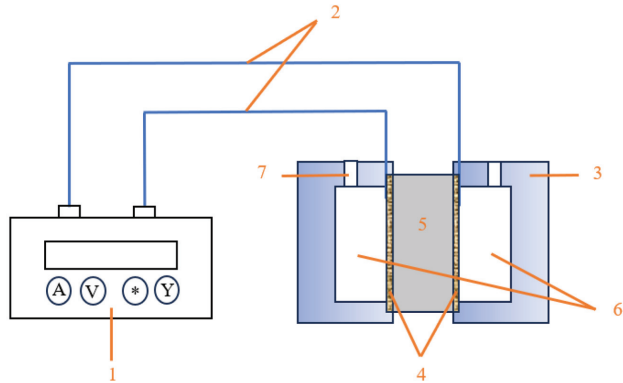


Figure 3: Schematic of the main structure principle of the AC measurement test apparatus. 1 – Concrete resistivity tester (1000 Hz, 1V); 2 – Wire; 3 – Testing tank; 4 – Copper mesh; 5 – Concrete specimen; 6 – 3.0 % NaCl solution; 7 – Liquid injection hole

RCM Method: The testing method is carried out according to the relevant specifications.

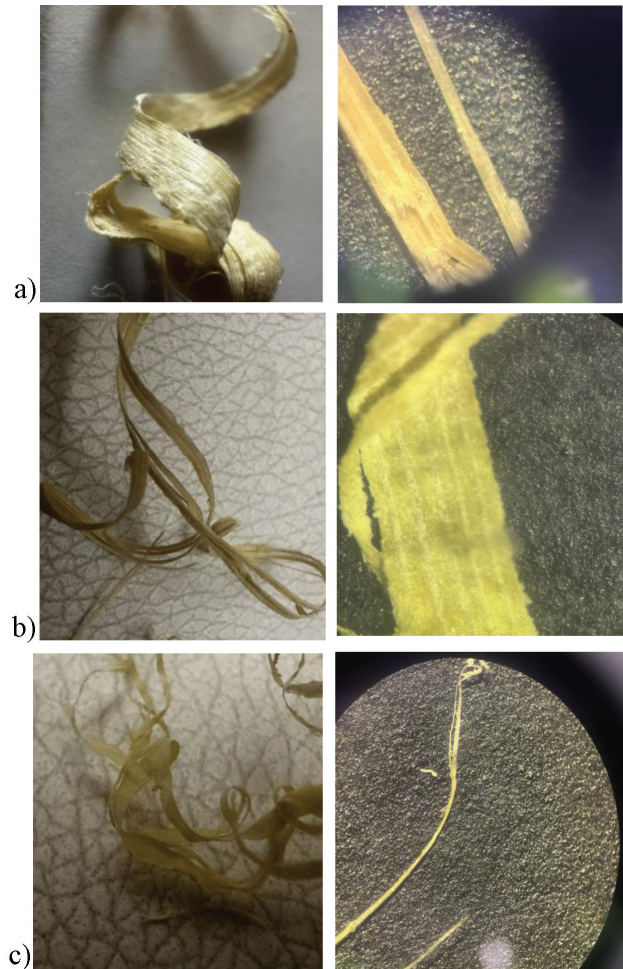


Figure 4: Microstructure of bamboo fibers: a) microstructure of bamboo fibers untreated, b) microstructure of bamboo fibers treated with calcium hydroxide, c) Microstructure of bamboo fibers treated with sodium hydroxide

boo fiber. On the other hand, sodium hydroxide solution is a strong alkaline solution that not only removes surface impurities but also disrupts the internal fiber structure of the bamboo, causing it to lose its inherent properties and, consequently, its ability to enhance the impermeability of concrete.

3.2 Analysis of the thermal stability of bamboo fibers

From **Figure 5** it can be observed that untreated bamboo fibers start to lose weight at 100 °C, and their mass decreases rapidly from 200 °C to 400 °C. After 400 °C, there is a slow decline until it reaches zero. Bamboo fibers treated with calcium hydroxide solution also experience a sharp decrease in mass between 200 °C and 400 °C, but after 400 °C, their mass gradually stabilizes, indicating that they have reached a stable state. Bamboo fibers treated with a strong sodium hydroxide solution exhibit a sharp decrease in mass after 200 °C, and their mass rapidly declines after 400 °C, reaching zero at around 600 °C.

Reasons for this phenomenon: Untreated bamboo fibers contain numerous impurities, and as the temperature changes, the quality of the bamboo fibers becomes unstable, especially in the presence of impurities like sugars and pectin. In contrast, bamboo fibers treated with calcium hydroxide solution have their impurities removed, leading to simpler composition and a more robust fiber structure, resulting in stable mass at later stages. However, bamboo fibers treated with sodium hydroxide solution undergo structural changes that disrupt their inherent properties. As the temperature rises, their mass rapidly decreases to zero, indicating that the internal fiber structure of the bamboo fibers has been compromised, making them unable to withstand temperature variations.

3.3 The influence of bamboo-fiber treatment methods on the chloride-ion permeability of concrete

After curing the specimens for 28 d, electric-flux experiments, AC tests, and RCM tests were conducted sep-

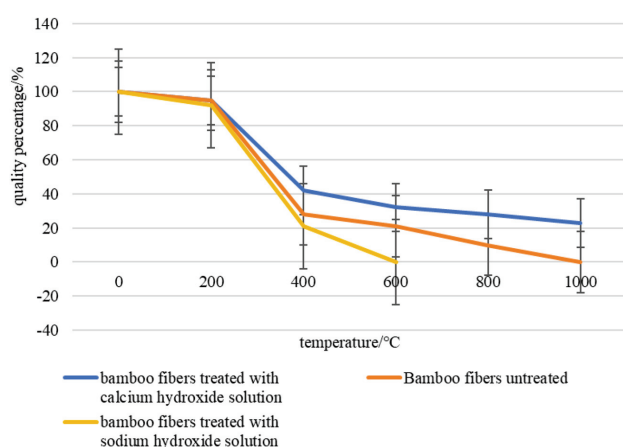


Figure 5: Thermal analysis of bamboo at different stages

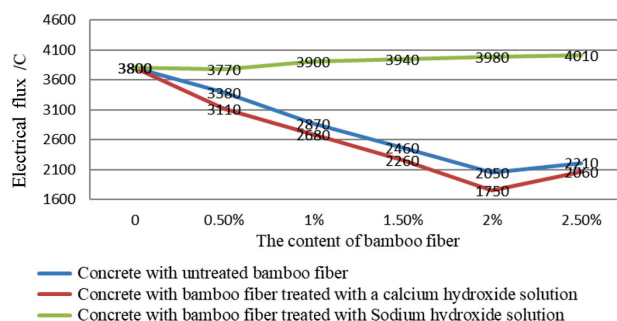


Figure 6: Electrical flux of bamboo-fiber concrete with different treatment methods and different incorporation ratios of fiber

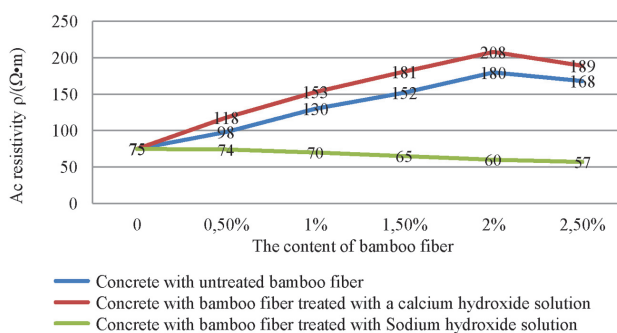


Figure 7: Relationship between different treatment methods and different content of bamboo fiber and resistivity

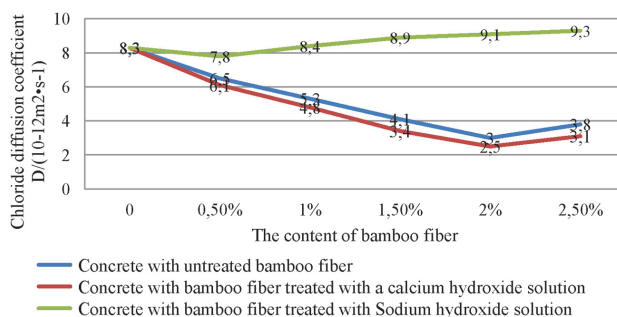


Figure 8: Relationship between different treatment methods and content of bamboo fiber and diffusion coefficient of chloride ion

arately. For each set of experiments, conduct three tests and take the average value as the result. Obtaining data related to electrical flux, electrical resistivity, and chloride-ion diffusion coefficients for concrete with varying amounts of bamboo fiber and different treatment methods. Present this data in the graphical representations as shown in **Figures 6 to 8**.

From **Figure 6** it can be observed that the electrical flux of the bamboo-fiber-reinforced concrete treated with calcium hydroxide solution is lower than that of the untreated bamboo-fiber-reinforced concrete, reaching the minimum values at a bamboo fiber content of 2 %, which are approximately 1750 °C and 2050 °C, respectively. This represents a reduction of around 14.6 % in electrical flux compared to untreated bamboo-fiber-reinforced concrete. On the other hand, concrete containing bamboo fibers treated with sodium hydroxide solution exhibits a higher electrical flux compared to untreated

bamboo-fiber concrete. The highest electrical flux is achieved at a bamboo fiber content of 2 %, reaching 4010 C, which is approximately 81 % higher than the electrical flux of untreated bamboo-fiber concrete. A lower electrical flux indicates better resistance to chloride-ion penetration, indicating that bamboo-fiber-reinforced concrete treated with calcium hydroxide solution significantly enhances the resistance to chloride-ion permeability. Concrete containing bamboo fibers treated with sodium hydroxide solution, on the contrary, exhibits a reduction in its resistance to chloride-ion penetration.

From **Figure 7** it can be seen that the AC resistivity of bamboo-fiber-reinforced concrete treated with calcium hydroxide solution is higher than that of untreated bamboo-fiber-reinforced concrete. The highest values are achieved at a bamboo-fiber content of 2 %, which are approximately 208 $\Omega\cdot\text{m}$ and 180 $\Omega\cdot\text{m}$, respectively. This indicates an increase of around 15.6 % in AC resistivity compared to untreated bamboo-fiber-reinforced concrete. Concrete containing bamboo fibers treated with sodium hydroxide solution, on the other hand, exhibits a lower AC resistivity compared to untreated bamboo-fiber concrete. The highest AC resistivity is achieved at a bamboo-fiber content of 2.5 %, measuring 57 $\Omega\cdot\text{m}$, which is approximately a 66 % reduction in AC resistivity compared to untreated bamboo-fiber concrete. Higher AC resistivity suggests better resistance to chloride-ion penetration, demonstrating that bamboo-fiber-reinforced concrete treated with calcium hydroxide solution enhances the resistance to chloride-ion permeability. Concrete containing bamboo fibers treated with sodium hydroxide solution, on the contrary, exhibits a reduction in its resistance to chloride-ion penetration.

From **Figure 8** it can be observed that the chloride-ion diffusion coefficient of bamboo-fiber-reinforced concrete treated with calcium hydroxide solution is lower than that of untreated bamboo-fiber-reinforced concrete. The lowest values are achieved at a bamboo-fiber content of 2 %, which are approximately 2.5 ($10^{-12}\text{m}^2\cdot\text{s}^{-1}$) and 3 ($10^{-12}\text{m}^2\cdot\text{s}^{-1}$), respectively. This represents a reduction of around 16.7 % in chloride-ion diffusion coefficient compared to untreated bamboo-fiber-reinforced concrete. Concrete containing bamboo fibers treated with sodium hydroxide solution exhibits higher chloride-ion diffusion coefficients compared to untreated bamboo-fiber concrete. The highest chloride-ion diffusion coefficient is achieved at a bamboo-fiber content of 2.5 %, measuring 9.3 ($10^{-12}\text{m}^2\cdot\text{s}^{-1}$), which is approximately a 144 % increase in chloride-ion diffusion coefficient compared to untreated bamboo-fiber concrete. A lower chloride-ion diffusion coefficient indicates better resistance to chloride-ion penetration, indicating that bamboo-fiber-reinforced concrete treated with calcium hydroxide solution significantly enhances the resistance to chloride-ion permeability. Concrete containing bamboo fibers treated with sodium hydroxide solu-

tion, on the contrary, exhibits a reduction in its resistance to chloride-ion penetration.

Based on the analysis above, all three experimental methods for chloride-ion permeability demonstrate that the addition of bamboo fibers treated with calcium hydroxide solution can improve the resistance to chloride-ion permeability in concrete. The improvement rate ranges between 14 % and 17 %, which further eliminates the errors introduced by individual experimental methods. Due to the existence of impurities such as pectin on the surface of bamboo fibers, calcium hydroxide is classified as a weak alkaline solution. the treatment with calcium hydroxide solution removes these impurities, increases the contact area between the bamboo fibers and concrete, and enhances the mechanical bond between them without damaging the fiber structure of the bamboo fibers. This treatment also reduces the porosity of the concrete, thus enhancing its resistance to chloride-ion permeability. Concrete with the addition of bamboo fibers treated with sodium hydroxide solution not only fails to improve its resistance to chloride-ion penetration but actually has a detrimental effect. This is because the sodium hydroxide solution is a strong alkaline solution, which can easily disrupt the fiber structure. While it removes impurities from the surface of the bamboo fibers, it also harms the inherent properties of the bamboo fibers. As a result, it not only fails to enhance the concrete's resistance to chloride ions but also reduces its durability.

3.4 The influence of bamboo-fiber content on chloride-ion permeability of concrete

From **Figure 6** it can be observed that the electric flux of the bamboo-fiber concrete treated with calcium hydroxide solution and untreated bamboo-fiber concrete both show a decreasing trend followed by an increasing trend with an increase in bamboo fiber content. The lowest values are achieved at a bamboo-fiber content of 2 %, which are 1750 C and 2050 C respectively. This represents a decrease of 54 % and 46 % in electric flux compared to the concrete without bamboo fibers. A lower electric flux indicates better resistance to chloride-ion permeability, suggesting an optimum bamboo fiber content of 2 % for the best anti-permeability performance to chloride ions. The continuous increase in electrical flux in concrete with bamboo fibers treated with sodium hydroxide solution indicates that the strong alkaline solution has disrupted the bamboo fiber structure, rendering it ineffective.

From **Figure 7** it can be observed that the AC resistivity of the bamboo-fiber concrete treated with calcium hydroxide solution and the untreated bamboo-fiber concrete both show an increasing trend followed by a decreasing trend with an increase in bamboo-fiber content. The highest values are achieved at a bamboo fiber content of 2 %, which are 208 $\Omega\cdot\text{m}$ and 180 $\Omega\cdot\text{m}$ respectively. This represents an increase of 177 % and 140 % in

AC resistivity compared to the concrete without bamboo fibers. A higher AC resistivity indicates better resistance to chloride-ion permeability, suggesting an optimum bamboo-fiber content of 2 % for the best anti-permeability performance to chloride ions. The continuous decrease in AC resistivity in concrete with bamboo fibers treated with sodium hydroxide solution suggests that the strong alkaline solution has disrupted the bamboo fiber structure, rendering it ineffective.

From Figure 8 it can be observed that the chloride-ion diffusion coefficient of the bamboo-fiber concrete treated with calcium hydroxide solution and the untreated bamboo-fiber concrete both show a decreasing trend followed by an increasing trend with an increase in bamboo-fiber content. The lowest values are achieved at a bamboo fiber content of 2 %, which are $2.5 \times 10^{-12} \text{ m}^2 \cdot \text{s}^{-1}$ and $3 \times 10^{-12} \text{ m}^2 \cdot \text{s}^{-1}$ respectively. This represents a decrease of 70 % and 64 % in chloride-ion diffusion coefficient compared to the concrete without bamboo fibers. A lower chloride-ion diffusion coefficient indicates better resistance to chloride-ion permeability, suggesting an optimum bamboo fiber content of 2 % for the best anti-permeability performance to chloride ions. The continuous increase in the chloride-ion diffusion coefficient in concrete with bamboo fibers treated with sodium hydroxide solution indicates that the strong alkaline solution has disrupted the bamboo-fiber structure, rendering it ineffective.

Based on the comprehensive analysis of the three different chloride-ion penetration-resistance tests, it is evident that for both untreated bamboo fibers and those treated with calcium hydroxide solution, as the bamboo-fiber content increases, the resistance to chloride-ion penetration initially increases and then decreases. The optimal resistance to chloride-ion permeability is achieved when the bamboo fiber content is 2 %, which avoids the errors introduced by individual experimental methods. Due to the microfiber structure and water-absorption characteristics of bamboo fibers, they can effectively fill the voids inside the concrete, reduce the porosity of the concrete, and block the permeation channels of chloride ions, thereby enhancing its resistance to permeability. The water-absorption effect of bamboo fibers also makes the interior of the concrete more compact, reducing the corrosion effects caused by internal moisture

and blocking the permeation and corrosion of chloride ions, further enhancing the resistance to chloride-ion permeability. In the case of bamboo fibers treated with sodium hydroxide solution, their fiber structure has been disrupted, making them unable to fill the internal voids of the concrete and losing their bonding function. This, in turn, reduces the concrete's resistance to chloride-ion penetration.

3.5 Correlation analysis of different experimental methods

To establish a linear relationship between the three different experimental methods, the resistivity of bamboo-fiber concrete was converted to conductivity, and then summarized with electric-flux and chloride-ion diffusion coefficient, as shown in Table 6. The linear fitting was performed using the least-squares method to obtain the linear models for conductivity and electric flux with respect to the chloride-ion diffusion coefficient (Figure 9).

From Figure 9 it can be observed that the electric-flux method, AC test method, and RCM method exhibit a strong correlation. Lower values of electric flux, electrical conductivity, and chloride-ion diffusion coefficient indicate better resistance to chloride-ion permeability in bamboo-fiber concrete. Additionally, there is a linear relationship among these variables, indicating the effectiveness of the three testing methods in evaluating the resistance to chloride-ion permeability when bamboo

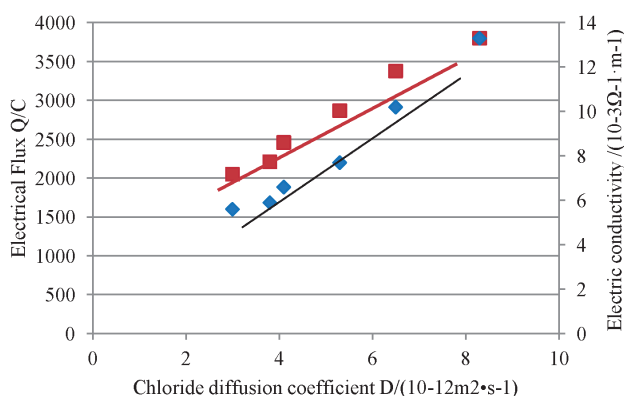


Figure 9: Linear models of conductivity and electric flux with respect to the chloride-ion diffusion coefficient

Table 6: Summary of three experimental results

Bamboo fiber content /%	Electric flux method		AC current test method			RCM method
	Electric flux /C	Permeability evaluation	Electrical resistivity /($\Omega \cdot \text{m}$)	Electrical conductivity /($10^{-3} \Omega^{-1} \cdot \text{m}^{-1}$)	Permeability evaluation	Chloride-ion diffusion coefficient $D/(10^{-12} \text{ m}^2 \cdot \text{s}^{-1})$
0	3800	high	75	13.3	high	8.3
0.5	3380	medium	98	10.2	high	6.5
1	2870	medium	130	7.7	medium	5.3
1.5	2460	medium	152	6.6	medium	4.1
2	2050	medium	180	5.6	low	3
2.5	2210	medium	168	5.9	medium	3.8

fibers are incorporated into concrete. Therefore, it is feasible to choose a relatively simple method for testing.

4 MECHANISM ANALYSIS

The permeability of concrete is primarily influenced by the size of its internal porosity.^{24–29} A higher porosity leads to poorer permeability, while a lower porosity enhances permeability. Concrete is composed of materials such as crushed stones, sand, and cement, and the contact surfaces between different mediums inevitably generate certain gaps.^{30–32} Additionally, the different production processes of concrete contribute to a certain proportion of porosity. Larger porosity negatively impacts the mechanical performance and the resistance to the chloride-ion permeability of concrete.³³

Bamboo fibers have a diameter of approximately 1–2 mm and a length of about 3–4 cm, exhibiting a certain tensile strength and ductility. Adding bamboo fibers to concrete can fill the internal voids of the concrete, compact its density, and thereby reduce its porosity, improving its resistance to chloride-ion permeability. The voids that affect the permeability of concrete mainly exist in the interfacial zone between the crushed stones and the cement. Due to the strip-like structure of these interfacial voids, chloride ions can find pathways for penetration. The strip-like structure of the bamboo fibers can bond the voids between the crushed stones and the cement contact zone, filling and bonding the voids resulting from the property differences between different mediums. This obstructs the penetration channels for chloride ions and enhances the resistance to the chloride-ion permeability of concrete. If the bamboo-fiber content is insufficient, the internal voids of the concrete cannot be adequately filled, resulting in an inadequate reduction of the porosity, and failing to maximize the improvement in resistance to chloride-ion permeability. On the other hand, excessive bamboo-fiber content lowers the rigidity and hardness of the concrete, diminishing its resistance to chloride-ion permeability. Only with an appropriate amount of bamboo fibers can the internal voids of the concrete be completely filled without affecting the overall rigidity and hardness, thereby maximizing the improvement in its resistance to chloride-ion permeability.

Due to the presence of impurities such as sugars and pectin on the surface of bamboo fibers, if bamboo fibers are directly added to concrete without surface treatment, during the initial formation of concrete, the bamboo fibers, along with the surface impurities, fill the voids in the concrete. However, as the subsequent hydration of cement in concrete progresses, the alkaline environment inside the concrete will dissolve the sugars and pectin on the surface of bamboo fibers, creating new voids. This, in turn, fails to enhance the resistance of concrete to chloride-ion permeability. Therefore, many researchers have explored different methods of surface treatment for

bamboo fibers. However, the treatment process is complex and costly. In this study, a calcium hydroxide solution and sodium hydroxide solution were used for the surface treatment of bamboo fibers. As the calcium hydroxide solution is a weak alkaline and less corrosive, it can remove impurities such as sugars and pectin from the surface of the bamboo fibers without damaging the fiber structure internally. The treatment enlarges the contact area between the inner fiber structure of bamboo fibers and the concrete, further enhancing the bonding capacity of bamboo fibers. This not only strengthens the bonding between bamboo fibers and different media contact zones in the concrete but also compacts the concrete, effectively reducing the porosity. At the same time, it avoids the dissolution of impurities on the surface of bamboo fibers during the subsequent cement hydration phase, thus preventing the formation of new voids. This ensures that the bamboo fibers do not undergo new chemical reactions with the age of the concrete, positively impacting the durability of the concrete and enhancing its resistance to chloride-ion permeability, with certain sustainability. On the other hand, a sodium hydroxide solution was used for surface treatment, which effectively removes the impurities on the surface of the bamboo fibers. However, since sodium hydroxide is a strong alkaline and corrosive substance, it damages the fiber structure of the bamboo fibers, resulting in weak bonding between the bamboo fibers and the voids in the concrete. As a result, it does not effectively improve the resistance of concrete to chloride-ion permeability.

5 CONCLUSIONS

This study observes the microstructure of bamboo fibers using optical microscopy and thermal analysis, and employs the electric-flux method, AC test method, and RCM method to determine the effect of adding bamboo fibers to concrete on its resistance to chloride-ion permeability. The following conclusions are drawn:

- (1) The surface impurities of bamboo fibers treated with calcium hydroxide solution are removed and the thermal stability of bamboo fibers are improved.
- (2) The bamboo fibers treated with sodium hydroxide solution have disrupted their fiber structure. While this treatment removed impurities from the surface of the bamboo fibers, it also damaged their inherent properties. As a result, it not only fails to enhance the concrete's resistance to chloride ions but also reduces its durability.
- (3) Bamboo fibers treated with calcium hydroxide solution not only remove surface impurities but also preserve the fiber structure. Compared to untreated bamboo fibers, they improve the resistance to chloride-ion permeability in concrete, with an enhancement rate between 14 % and 17 %.
- (4) The resistance to chloride-ion permeability of concrete shows an increasing trend with increasing bam-

boo-fiber content, reaching an optimal performance at a fiber content of 2 %.

(5) The electric-flux method, AC test method, and RCM method are mutually validating, showing good correlation. It is recommended to choose a suitable and simple method for testing purposes.

Bamboo fibers have been explored as a potential reinforcement material in concrete to enhance its mechanical properties, sustainability and overall performance. For future work on bamboo-fiber concrete could include: (i) material development and optimization – researchers should focus on optimizing the composition of bamboo-fiber concrete to achieve the best balance between strength, durability and workability; (ii) mechanical properties enhancement – continued efforts to enhance the mechanical properties of bamboo-fiber concrete, such as tensile strength, flexural strength, and impact resistance; and (iii) standardization and guidelines – the development of industry standards and guidelines for the use of bamboo fibers in concrete construction to ensure consistent quality and performance.

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