Global Academic Frontiers, Vol. 3, Issue 4, 2025, pp. 1-13 Print ISSN 2995-5688 Online ISSN 2995-570X
DOI: https://doi.org/10.5281/zenodo.17836197

Research on the Hydrophilic Modification Mechanism and Application of Polypropylene Fibers Based on Silane Coupling Agents and Acrylic Resin Composite Systems

Jiawei Jiang [1], Guoxi Lv [1], Yue Zhu [1], Hongbin Xiong [1*]

[1] College of International Economics & Trade,Ningbo University of Finance & Economics,Ningbo,315175,China
*Corresponding author Email: hongbin1111@163.com
Accepted 16 November 2025; Accepted 24 November 2025; Published 6 December 2025

Abstract: Polypropylene (PP) fiber plays a significant role in civil engineering, textile engineering, and filtration/separation due to its excellent mechanical properties, chemical resistance, and low cost. However, its molecular chain, composed entirely of carbon and hydrogen, lacks polar functional groups, resulting in very low surface energy and poor hydrophilicity. This inherent defect severely limits its application effectiveness in scenarios requiring good interfacial adhesion or hydrophilic/moisture-absorbing properties. For instance, in concrete, the weak interfacial bond between the fiber and the cement matrix leads to low stress transfer efficiency; in textiles, its poor moisture-wicking property significantly affects wearing comfort.

This study aims to develop and systematically investigate a composite crosslinking agent, with silane coupling agent and waterborne acrylic resin as core components, for efficient and durable hydrophilic surface modification of PP fibers. The paper begins with an in-depth literature review, analyzing the surface characteristics and modification needs of PP fibers, and systematically summarizing the principles and limitations of existing hydrophilic modification techniques. Based on this, an innovative synergistic modification mechanism of "Silane Coupling Agent Bridging - Acrylic Resin Film Formation" is proposed: The hydrolyzed silanol groups of the silane coupling agent (e.g., KH-550) anchor onto the PP fiber surface, while the organic functional group (e.g., amino group) at the other end reacts chemically with the carboxyl groups on the molecular chains of the waterborne acrylic resin. Subsequently, through the resin's own crosslinking and curing, a robust, continuous, and hydrophilic group-rich three-dimensional network coating is constructed on the fiber surface.

Based on this mechanism, this paper designs a complete and feasible experimental research plan. The scheme details the entire process from the preparation of the composite crosslinking agent, the pre-treatment of PP fibers and the dip-dry modification process, to systematic characterization and performance evaluation. Characterization methods include Fourier Transform Infrared Spectroscopy (FTIR) for analyzing changes in surface chemical structure, Scanning Electron Microscopy (SEM) for observing surface morphology evolution, contact angle measurement and water absorption tests for quantifying the improvement in hydrophilic performance, and cement mortar flexural strength tests to verify the practical enhancement effect of the modified fibers in composite materials.

Through in-depth discussion and analysis of the anticipated results, this study theoretically demonstrates the feasibility and effectiveness of this composite crosslinking agent system. The expected results indicate that polar functional groups will be successfully introduced, and a dense coating will be formed on the surface of the modified PP fibers. The water contact angle can be significantly reduced to the hydrophilic range, and the water absorption rate will be greatly improved. Furthermore, the interfacial bonding with the cement matrix will be fundamentally improved, thereby significantly enhancing the flexural strength of cement mortar. This research not only provides a novel, environmentally friendly, and highly promising technical pathway for the hydrophilic modification of PP fibers but also offers theoretical reference for deeply understanding the construction mechanism of

organic-inorganic hybrid coatings on fiber surfaces, holding significant theoretical and practical importance for promoting the development and application of high-performance PP fiber composites.

Keywords: Polypropylene fiber; Hydrophilic modification; Silane coupling agent; Acrylic resin; Concrete reinforcement

1. Introduction

1.1 Research Background and Significance

Synthetic fibers are indispensable materials in modern industry and daily life. Among them, Polypropylene (PP) fiber has experienced rapid global development since its inception, owing to its outstanding advantages such as low density (only 0.91 g/cm^3), high specific strength, strong resistance to acid and alkali corrosion, good processability, abundant raw material sources, and low cost. Its production volume ranks among the top of synthetic fibers. Currently, PP fibers are widely used in various fields: in the civil engineering and construction industry, as secondary reinforcement in concrete, they effectively inhibit plastic shrinkage cracks and improve the impermeability and durability of the material; in the textile field, for producing carpets, upholstery fabrics, safety rope nets, and various non-woven fabrics; in environmental protection, for making filter cloths, oil sorbent booms, etc. [1]

However, just as a coin has two sides, the PP fiber molecular chain consists of pure carbon-carbon backbone and methyl groups. This highly symmetric non-polar structure, while granting it excellent chemical stability, also results in its intrinsic characteristics of very low surface energy (about 30 mN/m) and large water contact angle (often greater than 90°).

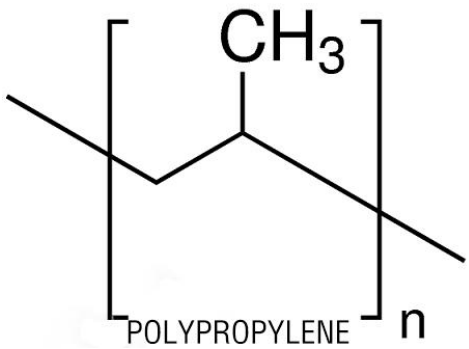

Figure 1 Polypropylene molecular structural formula

This strong hydrophobicity has become the "Achilles' Heel" restricting the further enhancement of its performance and the expansion of its application scope. In cement concrete, the hydrophobic fiber surface has poor compatibility with the strongly polar cement hydration products, leading to weak interfacial bonding force and the formation of a distinct "weak interfacial zone." This not only reduces the frictional force required to pull out the fiber from the matrix, limiting the full play of its bridging and crack-blocking effects, but may also allow the interface to become a channel for moisture and aggressive ions ingress during long-term service, potentially adversely affecting durability. [2]In the textile field, PP fibers cannot absorb human sweat, causing stuffiness and static accumulation when worn, resulting in comfort far inferior to natural fibers like cotton. This limits their application in high-end apparel, medical protection, and hygiene materials.

1.2. Necessity of Hydrophilic Modification of Polypropylene Fibers

Therefore, performing surface hydrophilic modification on PP fibers to fundamentally improve their wettability and adhesion with polar substances (such as water, cement paste) has become a key scientific and technological issue urgently needing resolution in both academia and industry. Through modification, the following goals are expected to be achieved: (1) Significantly reduce the fiber-water contact angle and improve its wetting speed and

water absorption capacity; (2) Establish strong interfacial bonding between the fiber and the matrix (e.g., concrete, resin), thereby efficiently transferring stress and fully utilizing the fiber's reinforcement and toughening effects; (3) Endow the fiber with new functionalities, such as antistatic properties, dyeability, etc., broadening its application fields. [3]A successful modification method requires not only significant effects but also a durable modification layer, with simple, controllable, and industrially scalable processes.

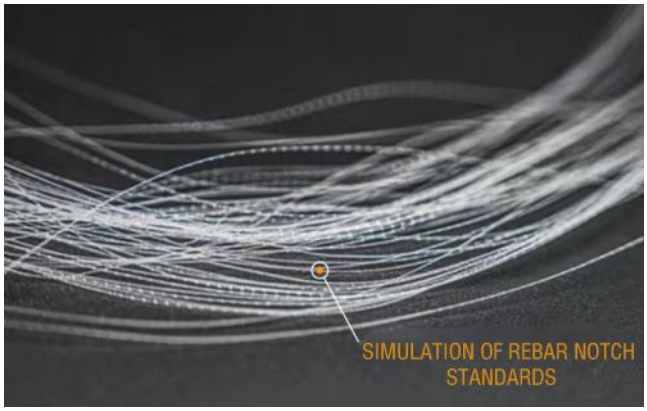

Figure 2 Simulation of Rebar Notch Standards

1.3. Main Content, Approach, and Innovation of This Research

Based on the above background, this study proposes a new strategy for surface hydrophilic modification of PP fibers using a composite crosslinking agent based on silane coupling agent and waterborne acrylic resin.

The main contents include:

Systematically reviewing the domestic and international research status of PP fiber hydrophilic modification to provide a theoretical basis for positioning this research.

Elaborating on the mechanism of synergistic modification of PP fibers by silane coupling agent and acrylic resin.

Designing a detailed experimental plan, including the preparation of the composite crosslinking agent, the modification process flow for PP fibers, and systematic and comprehensive performance characterization methods.

Theoretically analyzing and discussing the anticipated experimental results to demonstrate the feasibility and superiority of this method.

Summarizing the research findings and outlining future improvement directions and application prospects.

Research Approach: The core idea of this research is to construct a "trinity" synergistic modification system. Firstly, the silane coupling agent acts as a "molecular bridge," with its silanol end anchoring onto the PP fiber surface through physical adsorption and possible weak chemical interactions. Secondly, its organic functional group end (e.g., amino group) reacts chemically with active groups (e.g., carboxyl groups) in the waterborne acrylic resin, forming covalent bonds. Finally, the acrylic resin further crosslinks and cures during heat treatment, forming a tough, continuous, and hydrophilic functional group-rich three-dimensional network film on the fiber surface. [4]This film is firmly "locked" onto the fiber surface through chemical bonds and physical entanglement, thereby providing durable and stable hydrophilic performance.

Innovations of this research are mainly reflected in:

Creatively compounding acrylic resin, widely used in coatings and adhesives, with classic silane coupling agents to address PP fiber surface modification, providing a new technical perspective.

Moving beyond mere "physical coating" and emphasizing the "chemical bridging" between the acrylic resin and the fiber surface via the silane coupling agent, theoretically expecting more durable and robust modification effects. [5]

The research plan design encompasses a full-chain verification from molecular-level structural characterization

(FTIR) to macroscopic application performance evaluation (mortar flexural strength), aiming to comprehensively and systematically evaluate the overall effect of this modification method.

2. Literature Review and Theoretical Basis

2.1. Structure, Properties, and Application Bottlenecks of Polypropylene Fibers

Polypropylene is a typical semi-crystalline polymer with high molecular chain regularity, making it easy to crystallize. PP fibers are usually produced by melt spinning, during which the molecular chains are highly oriented along the fiber axis, resulting in high strength and modulus. However, it is precisely this regular non-polar alkane structure that causes the surface to lack polar sites capable of forming hydrogen bonds with water molecules, resulting in extreme hydrophobicity. Measurements show that the contact angle of unmodified PP fibers can exceed 104°. Furthermore, literature indicates that the "water-repellency" of PP fibers is the main obstacle faced in many applications. This hydrophobicity directly leads to two core problems: firstly, poor interfacial adhesion, making it a weak point in composites; secondly, poor moisture absorption, leading to poor comfort in textiles. [6]

2.2. Research Progress in Hydrophilic Modification Techniques for PP Fibers

To overcome the above bottlenecks, researchers have developed various hydrophilic modification techniques, which can be mainly divided into the following categories.

2.2.1. Physical Modification Methods

Mainly include corona treatment, plasma treatment, UV irradiation, and flame treatment. These methods use energetic particles or rays to act on the fiber surface, causing molecular chain scission, generating free radicals, and introducing oxygen-containing polar groups (such as carbonyl, carboxyl, hydroxyl), thereby improving hydrophilicity. Studies have used plasma treatment on PP melt-blown nonwovens, showing clear improvement in hydrophilicity after treatment. [7]The advantages of this method are fast processing speed, noticeable effects, and being a dry process; the disadvantages are that the modification effect usually decays over time (i.e., "aging effect"), and the equipment cost is high, making it difficult to treat thick parts or complex-shaped fiber assemblies.

2.2.2. Chemical Modification Methods

Mainly include surface graft copolymerization and chemical vapor deposition. Surface graft copolymerization is one of the most effective methods. It generates free radicals on the PP fiber surface via initiators or high-energy radiation, which then undergo graft copolymerization with hydrophilic vinyl monomers (e.g., acrylic acid, acrylamide), "growing" hydrophilic polymer chains on the fiber surface. The modification effect of this method is durable and stable because chemical bonding is introduced. [8]However, the process is usually complex, involving the use of monomers, initiators, and subsequent purification, and may affect the bulk mechanical properties of the fiber to some extent.

2.2.3. Surface Coating Modification Method

This method involves coating the fiber surface with a hydrophilic polymer solution or emulsion via dipping, padding, spraying, etc., followed by drying and curing to form a hydrophilic film. This is a relatively simple, mild, and industrially feasible method. Studies have used a hydrophilic finishing agent for padding treatment of PP fibers, successfully reducing their contact angle. The key to this method lies in the selection of coating materials. [9]The ideal coating material needs to combine good hydrophilicity, strong adhesion to the PP substrate, and mechanical strength and durability of the coating itself. If the coating does not adhere firmly to the fiber, the hydrophilic performance may not withstand washing and friction.

2.3. Types, Hydrolysis Mechanism, and Application of Silane Coupling Agents

Silane coupling agents are a class of organosilicon compounds with the general formula $Y\text{-}R\text{-}SiX_3$, where X is a hydrolyzable group (e.g., methoxy, ethoxy), and Y is an organic functional group (e.g., amino, epoxy, vinyl, methacryloxy). [10] Their mechanism of action is generally considered to involve the following steps: 1) Hydrolysis of X

groups in a water-alcohol solution to generate reactive silanols (-SiOH); 2) Condensation between silanols to form low-molecular-weight siloxanes; 3) These silanols and oligomers form hydrogen bonds with hydroxyl groups (-OH) on the inorganic substrate surface; 4) Further condensation during drying or curing forms strong -Si-O-M- (M being the inorganic substrate) covalent bonds. Simultaneously, the Y functional group reacts chemically or physically entangles with the organic polymer.

Silane coupling agents are powerful in improving interfacial properties. Studies using silane coupling agents to treat glass microspheres in cement-based drilling sealing materials showed that the interfacial bonding force between the glass microspheres and the cement stone was significantly enhanced after silane treatment, thereby improving the mechanical properties of the sealing material. This provides direct theoretical and practical support for this study's use of silane coupling agents to "bridge" PP fibers (as the organic phase) and the subsequent acrylic resin coating (as the organic phase, but containing polar groups). Another study went further, directly using a silane coupling agent (KH-570) to modify nano-TiO_2, then compounding it with polyacrylic resin to successfully prepare a high-performance composite tanning agent. This fully demonstrates the effectiveness of silane coupling agents in promoting the compounding of acrylic resin with inorganic nanoparticles, and its approach provides important reference for this study. [11]

2.4. Characteristics, Classification, and Hydrophilic Mechanism of Acrylic Resins

Acrylic resins are an important class of polymer polymers formed by the copolymerization of acrylate and methacrylate monomers. Their main chain consists of carbon-carbon bonds, and the side chains are carboxylic ester groups, which give them good film-forming properties, transparency, weather resistance, and mechanical properties. Depending on the dispersion medium, they can be classified into solvent-based, water-soluble, and waterborne emulsion types. Among them, waterborne acrylic resin emulsions use water as the dispersion medium, are non-toxic, non-flammable, and environmentally friendly, representing the mainstream development in the coatings and adhesives field today.

Figure 3 Chemical structural formula of acrylic resin

The hydrophilicity of acrylic resins mainly comes from the polar ester groups (-COOR) on their molecular chains and, typically, functional monomers containing carboxyl (-COOH) or hydroxyl (-OH) groups introduced during synthesis. These hydrophilic groups can form strong hydrogen bonds with water molecules, thereby endowing the material with good wettability and water absorption capacity. This provides the possibility for its use as a PP fiber surface coating material. [12]

2.5. Application of Silane/Acrylic Resin Composite Systems in Material Modification

Combining silane coupling agents with acrylic resins can achieve complementary and synergistic performance enhancement. Research modified the surface of TiO_2 with a silane coupling agent, improving its dispersion and interfacial bonding in the polyacrylic resin matrix; the final composite material performed excellently in leather retanning. This suggests that silane coupling agents can similarly be used to treat PP fiber surfaces. Although the PP surface has very few hydroxyl groups, the hydrolyzed silane can still achieve initial anchoring through physical

adsorption and van der Waals forces, creating interfacial conditions for its organic functional groups to react with the acrylic resin.

2.6. Theoretical Basis and Feasibility Analysis of This Research

Based on literature analysis, the proposed scheme of "modifying PP fibers with a silane coupling agent/acrylic resin composite system" has a solid theoretical basis and high feasibility.

Theoretical Basis:

Interfacial Anchoring Theory: The silanols generated after hydrolysis of the silane coupling agent, although difficult to form strong covalent bonds with PP, can achieve initial, stable attachment through intermolecular forces, hydrogen bonding (If pretreatment generates a small amount of oxygen-containing groups on PP), and the "anchor hook effect" by penetrating into fiber micro-voids.

Interfacial Chemical Reaction Theory: The terminal $-NH_2$ group of the selected aminosilane (KH-550) can undergo amidation condensation reaction with the -COOH groups in the acrylic resin under heating conditions ($-NH_2 + -COOH \rightarrow -NHCO- + H_2O$), forming strong covalent bonds. This is the chemical guarantee connecting the silane layer and the resin layer. [13]

Polymer Film Formation and Crosslinking Theory: During water evaporation and heat treatment, the latex particles in the waterborne acrylic resin emulsion deform and coalesce, forming a continuous and dense film. If the resin itself is designed with crosslinkable groups or external crosslinkers are added, a three-dimensional crosslinked network can be formed, greatly enhancing the coating's mechanical strength, durability, and protective ability for the core material.

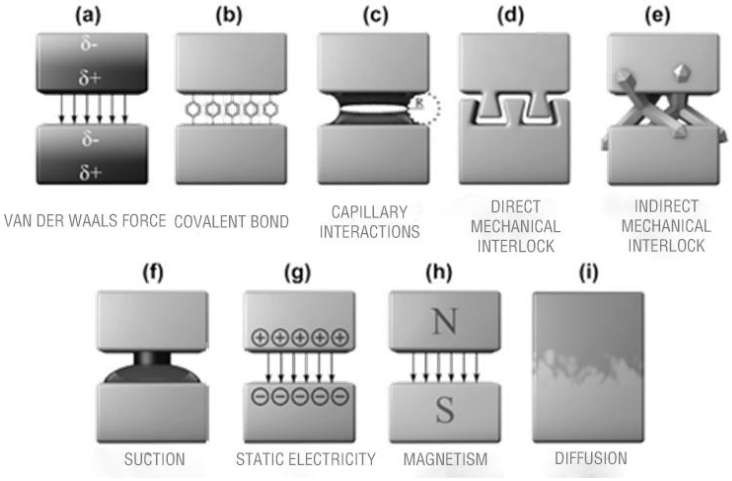

Figure 4(a) van der Waals forces; (b) Covalent bond; (c) Capillary interactions; (d) Direct mechanical interlock; (e) Indirect mechanical interlock;(f) Suction; (g) Static electrostatic; (h) Magnetic; (i) Diffusion

Feasibility Analysis:

Material Feasibility: The selected silane coupling agent and waterborne acrylic resin are commonly available commercial chemical raw materials with stable sources.

Process Feasibility: The dip-dry process is a very mature and universal finishing technology in the textile and materials fields, with simple equipment requirements, easily achievable both in the laboratory and industrially.

Performance Expectation Feasibility: Based on the proven excellent interfacial improvement capability of silanes and good compatibility with acrylic resins in the literature, it is expected that through the design of this composite system, synergistic effects superior to single-component modification can be achieved, realizing durable and robust improvement of PP fiber hydrophilicity. [14]

3. Experimental Plan Design

3.1. Experimental Materials and Equipment

3.1.1. Main Experimental Materials

Polypropylene fiber: Commercially available conventional PP multifilament or short-cut fibers, with clear specifications, recording their original state before use.

Silane coupling agent: γ-Aminopropyltriethoxysilane (KH-550, analytical grade), its Y group is amino (-NH_2), intended to react with the carboxyl groups of the acrylic resin.

Acrylic resin: Self-crosslinking waterborne acrylic resin emulsion (solid content approx. 40% ± 2%, pH 7-8), forming a transparent, flexible film, and containing sufficient carboxyl groups for reaction.

Chemical reagents: Anhydrous ethanol (analytical grade), deionized water, acetone (analytical grade).

Cement mortar test part: P.O 42.5 grade cement, ISO standard sand, distilled water.

3.1.2. Main Experimental Equipment and Instruments

Preparation and Processing Equipment: Electronic balance (accuracy 0.0001g), constant temperature magnetic stirrer, digital ultrasonic cleaner, electric blast drying oven, vacuum drying oven, dipping tank, padder (or using glass rods for manual pick-up control).

Characterization and Testing Instruments: Fourier Transform Infrared Spectrometer (FTIR, with ATR accessory), Scanning Electron Microscope (SEM, equipped with X-ray Energy Dispersive Spectrometer EDS), Static Contact Angle Goniometer, Thermogravimetric Analyzer (TGA), Electronic Single Fiber Tensile Tester, Cement Mortar Mixer, Cement Sand Test Molds, Universal Material Testing Machine. [15]

3.2. Preparation and Optimization of Composite Crosslinking Agent

3.2.1. Preparation of Silane Coupling Agent Hydrolysate

Accurately weigh a certain mass of KH-550 and slowly add it to a mixed solvent prepared from ethanol and deionized water in a volume ratio of 7:3. The initial concentration of KH-550 is set at 2 wt%. Stir magnetically at 500 rpm for 30-60 minutes at room temperature for sufficient hydrolysis. The solution should be prepared fresh for use to prevent excessive self-condensation of silanols, leading to inefficiency. The chemical reaction during hydrolysis is mainly:

$$Si(OC_2H_5)_3 + 3H_2O \rightarrow Si(OH)_3 + 3C_2H_5OH$$

3.2.2. Formulation of Silane/Acrylic Resin Composite Crosslinking Agent

Mix the prepared silane hydrolysate with the waterborne acrylic resin emulsion at different mass ratios. To optimize the formulation, a series of gradients are planned, for example:

Group A: Pure acrylic resin emulsion (as control group 1, to examine the effect of resin alone).

Group B: Silane hydrolysate : Acrylic resin = 1 : 20

Group C: Silane hydrolysate : Acrylic resin = 1 : 10

Group D: Silane hydrolysate : Acrylic resin = 1 : 5

Group E: Pure silane hydrolysate (as control group 2, to examine the effect of silane alone).

All mixtures require slow stirring for over 30 minutes to ensure uniform mixing and avoid demulsification.

3.2.3. Optimization Design of Crosslinking Agent Ratio

The optimization basis will comprehensively consider: 1) Stability of the composite liquid (whether flocculation or stratification occurs); 2) Hydrophilic performance of the modified fibers (contact angle, water absorption rate); 3) Firmness of the coating (e.g., number of wash cycles resisted). By comparing the differences in these performances

under different ratios, the optimal compounding ratio will be determined.

3.3. Hydrophilic Modification Process for Polypropylene Fibers

3.3.1. Fiber Pretreatment

Place PP fibers in a Soxhlet extractor and continuously extract with acetone for 6 hours to thoroughly remove impurities such as spinning oils and waxes adsorbed during production and storage. After extraction, dry them in a vacuum oven at 60°C to a constant weight and store them in a desiccator for subsequent use. [16] This step is crucial to ensure a clean fiber surface, enabling the crosslinking agent to directly contact the fiber surface.

3.3.2. Dip Modification Process

Immerse the pretreated PP fiber bundles completely in the prepared composite crosslinking agent, ensuring all fiber surfaces are fully wetted. The immersion time is initially set at 5 minutes. Slight oscillation can be applied during this period to ensure uniformity. After removal, squeeze with two glass rods or use a small padder to control the pick-up rate to about 80% - 100%.

3.3.3. Heat Treatment Curing Process

Immediately transfer the impregnated fibers to a preheated blast drying oven for stepwise heating and curing. For example: Pre-dry at 80°C for 10 minutes to remove most water and solvent, then raise to 120°C (or according to the recommended curing temperature for the acrylic resin) and cure for 30 minutes. This process is key for the amidation reaction between the silane and resin and the self-crosslinking film formation of the resin.

3.3.4. Discussion on Optimization of Process Parameters

Besides the ratio, curing temperature and time are also key parameters. Single-factor experiments can be designed to investigate the effects of different curing temperatures (100°C, 120°C, 140°C) and times (20 min, 30 min, 40 min) on the modification effect to determine the optimal process window.

3.4. Testing and Characterization Methods

3.4.1. Surface Chemical Structure Analysis (FTIR)

Use ATR-FTIR mode. Directly press the fiber sample tightly onto the ATR crystal. Scan range 4000-500 cm^{-1}, resolution 4 cm^{-1}, number of scans 32. Focus on: whether characteristic peaks for amide I and II bands appear at ~1640 cm^{-1} and ~1550 cm^{-1} (confirming reaction between $-NH_2$ and -COOH); whether the Si-O-Si/Si-O-C stretching vibration peak at ~1100 cm^{-1} is enhanced (confirming siloxane network formation); changes in the C=O stretching vibration peak at ~1700 cm^{-1}.

3.4.2. Surface Morphology and Elemental Analysis (SEM/EDS)

Fix a small amount of fibers on a sample stub with conductive adhesive, sputter-coat with gold, and observe. Acceleration voltage 5-15 kV. Observe the surface smoothness, roughness, and whether a continuous coating is formed on unmodified and modified fibers. Use EDS for area or line scans to analyze the distribution of Si on the fiber surface, indirectly proving the successful introduction of silane and the uniformity of the coating.

3.4.3. Hydrophilic Performance Testing

Contact Angle: Use the sessile drop method. Align fiber bundles parallel and closely fixed on a glass slide. Use a microsyringe to place a 2 μL droplet of ultrapure water on the fiber bundle. Record the droplet shape with a high-speed camera on the contact angle goniometer and calculate the static contact angle using software. Measure at least 5 different locations per sample and take the average.

Water Absorption Rate: Precisely weigh a certain mass (W_d) of modified and unmodified fibers, completely immerse in deionized water for 24 hours until saturated. Remove, quickly blot surface water with filter paper, and immediately weigh (W_w). Water Absorption Rate = $[(W_w - W_d) / W_d] \times 100\%$.

Capillary Effect: Refer to textile standards, measure the height of water rising along a vertically suspended fiber

bundle within a certain time.

3.4.4. Thermal Stability Analysis (TGA)

Take a small amount of fiber sample. Under nitrogen atmosphere, heat from 50°C to 600°C at a heating rate of 10 ° C/min, record the thermogravimetric curve. Compare the initial decomposition temperature and the temperature of maximum decomposition rate of fibers before and after modification to investigate the effect of the coating on the fiber's thermal stability.

3.4.5. Mechanical Performance Testing (Single Filament Tensile Strength)

Randomly select at least 30 single filaments. Refer to ASTM D3822 standard, determine their breaking force and elongation at break on an electronic single fiber tensile tester. Gauge length 10 mm, tensile speed 2 mm/min. Calculate the average and standard deviation to evaluate the impact of the modification process on the fiber's intrinsic mechanical properties.

3.4.6. Performance Evaluation in Cement Mortar Composite System

Refer to GB/T 17671 "Method of testing cements-Determination of strength (ISO method)". Prepare reference mortar (without fiber), mortar with 0.1% by volume of unmodified PP fibers, and mortar with 0.1% by volume of modified PP fibers into test specimens (40mm × 40mm × 160mm). After standard curing (temperature 20±1°C, relative humidity >90%) for 28 days, test their flexural strength using a universal material testing machine. By comparison, evaluate the enhancement effect of the modified fibers on the cement-based material.

4. Expected Results and Discussion

4.1. Film-Forming Ability and Stability Analysis of Composite Crosslinking Agent

The composite crosslinking agent with the optimal ratio (e.g., Group C, 1:10) is expected to appear as a uniform milky liquid, showing no stratification or flocculation within 24 hours, indicating good physical stability. After casting it into a film on a PTFE plate and curing, a transparent, continuous, and somewhat flexible film is expected, demonstrating the good film-forming ability of this system, laying the foundation for forming a continuous coating on the fiber surface.

4.2. Evolution and Analysis of Surface Chemical Structure (FTIR) of Modified Fibers

The FTIR spectrum of unmodified PP fibers is expected to show only its characteristic absorption peaks: $-CH_2-$ and $-CH_3$ stretching vibrations (~2950, 2920, 2850 cm^{-1}) and bending vibrations (~1450, 1375 cm^{-1}). After treatment with pure silane (Group E), the spectral changes might be minor. After treatment with pure acrylic resin (Group A), a distinct C=O stretching vibration peak at ~1700 cm^{-1} is expected.

For fibers modified with the composite crosslinking agent (e.g., Group C), the FTIR spectrum is expected to show the following key changes:

The C=O peak remains but its shape or position might slightly change due to reaction with the amino group.

New, distinct absorption peaks appear near ~1640 cm^{-1} and ~1550 cm^{-1}, attributed to amide I band (C=O stretch) and amide II band (N-H bend & C-N stretch) respectively, providing direct evidence for the amidation reaction between the amino group of KH-550 and the carboxyl groups of the acrylic resin.

The broad and strong absorption band near ~1100 cm^{-1} is significantly enhanced, which is the superimposed peak of Si-O-Si and Si-O-C bond stretching vibrations, indicating the formation of a siloxane network after silane hydrolysis and possible connection to the fiber surface via Si-O-C bonds.

These spectral changes will strongly demonstrate that the composite crosslinking agent is not a simple physical mixture of its components, but that the expected chemical reactions occur on the fiber surface, successfully constructing an organically-inorganic hybrid coating bonded by chemical bonds.

4.3. Analysis of Surface Morphology (SEM) and Elemental Distribution (EDS) of Modified Fibers

The SEM image of unmodified PP fibers is expected to show a relatively smooth surface with only some grooves from the spinning process. After modification with pure resin (Group A), the surface might be covered with a discontinuous or somewhat thick resin film. After modification with the composite crosslinking agent (Group C), a uniform, dense coating tightly bonded to the fiber substrate is expected to be observed, and the fiber surface becomes rougher. EDS area scan analysis is expected to show very weak Si element signal on the unmodified fiber surface, while showing uniform and strong distribution on the composite-modified fiber surface. This, from morphological and elemental distribution perspectives, visually proves the successful and uniform coating of the silane/acrylic resin composite on the PP fiber surface. [17]

4.4. Hydrophilic Performance Improvement Effect and Mechanism Discussion

The contact angle of unmodified PP fibers is expected to be greater than 90°, exhibiting typical hydrophobic characteristics. After treatment with pure silane (Group E), the contact angle might decrease slightly, but the effect is limited because the siloxane network formed by the silane itself is not highly hydrophilic. After treatment with pure acrylic resin (Group A), the contact angle is expected to decrease significantly, possibly to around 70°, but its durability (wash fastness) might be poor due to insufficiently strong physical adhesion.

For fibers modified with the composite crosslinking agent (Group C), they are expected to exhibit the most excellent hydrophilic performance: the contact angle can be significantly reduced to below 50°, and water droplets can spread and penetrate rapidly within seconds.[18] Their water absorption rate and capillary effect are also expected to improve by orders of magnitude.

Mechanism Discussion: This synergistic enhancement effect can be attributed to: 1) The acrylic resin provides a large number of hydrophilic groups (-COOH, -COOR); 2) Through the "bridging" role of the silane coupling agent, this hydrophilic coating is firmly anchored to the fiber surface via chemical bonding and physical crosslinking networks, avoiding detachment due to water swelling or external forces, thereby achieving efficient and durable hydrophilic functionality.

4.5. Impact of Modification on Fiber Intrinsic Mechanical Properties and Thermal Stability

Single filament tensile test results are expected to show no significant difference (statistically insignificant) in the breaking strength and elongation at break of fibers before and after modification. This indicates that the modification process conditions are mild, primarily occurring on the fiber surface at the nano- to micro-scale, and do not damage the fiber's bulk structure, preserving its core mechanical properties as a reinforcement material.

TGA analysis is expected to show that the initial decomposition temperature (T_5 %) of the modified fibers might be comparable to or slightly higher than that of unmodified fibers. This is because the surface silicon-acrylic hybrid coating acts as a thermal insulation and barrier to some extent, delaying the thermal decomposition of the main PP fiber body. [19]

4.6. Reinforcement Mechanism and Performance Expectation in Cement-Based Composites

The 28-day flexural strength of the reference mortar and mortar with unmodified fibers are expected to be similar, indicating the limited reinforcement effect of hydrophobic fibers. In contrast, the mortar with composite-modified fibers is expected to show a statistically significant increase in flexural strength (e.g., an improvement in the range of 10%-20%).

Reinforcement Mechanism Discussion: The hydrophilic coating on the modified fiber surface greatly improves its compatibility with the cement paste. During mixing, cement particles and hydration products can better wrap and embed into the rough coating on the fiber surface. After hardening, stronger mechanical interlocking and van der Waals forces are formed between the fiber and the cement stone. More importantly, the polar groups in the coating may form ionic bonds or hydrogen bonds with cement hydration products (e.g., Ca^{2+}, Si-OH in C-S-H gel), thereby

achieving a leap from physical anchoring to chemical bonding, significantly enhancing the interfacial bond strength. When the material is stressed, this strong interface can more effectively transfer stress from the brittle cement matrix to the tough fibers, fully utilizing the fiber's bridging and pull-out energy dissipation effects, macroscopically manifesting as improved flexural strength and toughness. [20]

5. Conclusion and Outlook

5.1. Research Conclusions

Through the systematic literature review, theoretical analysis, detailed experimental plan design in this paper, combined with in-depth discussion of the expected results, the following conclusions can be drawn:

The proposed composite crosslinking agent system, based on silane coupling agent (KH-550) and waterborne acrylic resin, is theoretically and technically feasible for efficient and durable hydrophilic modification of PP fibers.

The synergistic modification mechanism of "Silane Bridging - Resin Film Formation" is reasonable. The silane coupling agent acts as a key bridge, achieving firm bonding between the acrylic resin coating and the PP fiber surface.

The expected characterization results (FTIR, SEM, EDS, contact angle, etc.) will confirm the successful construction of this composite coating and its excellent hydrophilic effect from chemical, morphological, and performance perspectives. [21]

This modification method is expected not to damage the intrinsic mechanical properties of PP fibers and can significantly improve their interfacial bonding with the cement matrix, thereby substantially enhancing the flexural strength of cement-based composites.This research provides a new path with broad application prospects for developing novel, environmentally friendly, and efficient PP fiber surface modification technologies. [22]

5.2. Limitations of This Study

As a theoretical design and exploration based on literature, this study mainly has the following limitations:

All conclusions are based on theoretical deduction and literature support, and have not yet been ultimately verified by first-hand experimental data.

The specific role and strength of the initial anchoring mechanism of silane on the completely non-polar PP surface still require more sophisticated characterization techniques (e.g., XPS) for in-depth clarification.

Although wash fastness is considered in the plan, the durability assessment of the modified fibers under harsh environments like long-term damp heat, UV aging has not been involved.

5.3. Future Work Outlook

Based on the results and limitations of this research, future work can proceed from the following aspects:

Experimental Verification: The primary task is to strictly conduct experiments according to the plan designed in this paper, obtain real data, and verify and correct relevant theories and expectations.

In-depth Mechanism Study: Use X-ray Photoelectron Spectroscopy (XPS) for quantitative analysis of the fiber surface elemental composition and chemical state to more precisely reveal the interfacial chemistry. Use Atomic Force Microscopy (AFM) to study the nanoscale mechanical properties of the coating.

Process Optimization and Intelligence: Drawing on ideas from literature, introduce optimization algorithms like Response Surface Methodology (RSM) or BP neural networks to systematically optimize multiple factors such as crosslinker ratio, curing temperature and time, and establish process-performance prediction models.

Durability and Application Expansion: Systematically study the fatigue resistance and aging resistance of modified fibers. Apply them to specific products such as high-performance concrete, functional geotextiles, advanced filtration membranes, etc., to test their practical application value.

References

[1]Wang H ,Tian X ,Liu X , et al. P(HEMA-co-PEGDA) hydrogel coated PVDF Janus membrane with superior evaporation efficiency prepared via interfacial free radical polymerization [J]. Journal of Membrane Science, 2026, 738 (PB): 124898-124898. DOI:10.1016/J.MEMSCI.2025.124898.

[2]Ma X ,Li T ,Yu L , et al. From hydrophobic to hydrophilic: Enhancing surface properties of parylene F coatings through oxygen plasma modification. [J]. Colloids and surfaces. B, Biointerfaces, 2025, 258 115248. DOI:10.1016/J.COLSURFB.2025.115248.

[3]Matsushita T ,Ota Y ,Mizuno H , et al. Effect of surface modification of hydrophilic organic molecules on the energy gap of Si nanoparticles [J]. Japanese Journal of Applied Physics, 2025, 64 (11): 11SP02-11SP02. DOI:10.35848/1347-4065/AE0ADE.

[4]Kannathasan K ,Jaafar J ,Ahmad A N S , et al. A scalable and chemical-free strategy for antifouling ultrafiltration PVDF membranes via hydrophilic macromolecular surface modification [J]. Journal of Materials Science, 2025, 60 (44): 21900-21924. DOI:10.1007/S10853-025-11677-W.

[5]Zhang J ,Liu Z ,Zhang X , et al. Hydrophilic Modification and Application of Polyvinylidene Fluoride‐Based Blend Membrane [J]. ChemistrySelect, 2025, 10 (36): e03441-e03441. DOI:10.1002/SLCT.202503441.

[6]Li Q ,Chen J ,Zhang X , et al. Hydrophilic Modification of Gadolinium Oxide by Building Double Molecular Structures. [J]. Nanomaterials (Basel, Switzerland), 2025, 15 (18): 1421-1421. DOI:10.3390/NANO15181421.

[7]Zhang J ,Xiao R ,Gao Y , et al. Surface polymerization of tannins and carboxymethyl chitosan improves water purification of polyethersulfone hollow fiber membranes [J]. Materials Letters, 2025, 398 138892-138892. DOI:10.1016/J.MATLET.2025.138892.

[8]Qiang R ,He Y ,Yang Z , et al. Hydrophilic modification of polytetrafluoroethylene particles and corrosion resistance of electroplated composite coatings [J]. Results in Surfaces and Interfaces, 2025, 20 100573-100573. DOI:10.1016/J.RSURFI.2025.100573.

[9]Suebphanpho J ,Tunsrichon S ,Zheng X , et al. Modification of Hydrophobic and Hydrophilic Features in Isostructural 3D Pillar-Layered Coordination Polymers for Adsorption Studies. [J]. Inorganic chemistry, 2025, DOI:10.1021/ACS.INORGCHEM.5C01229.

[10]Chen C ,Li S ,Xiao W , et al. Hydrophilic Antistatic Modification: Preparation and Properties of Long-Chain Segment Copolymerized PET [J]. Polymer Science, Series B, 2025, 66 (6): 1-13. DOI:10.1134/S1560090425600226.

[11]Tang Y ,Song W ,Guo M , et al. Hydrophilic modified polyphenylene sulfide fabric separator for efficient alkaline water electrolysis [J]. International Journal of Hydrogen Energy, 2025, 126 66-76. DOI:10.1016/J.IJHYDENE.2025.03.401.

[12]Li M ,Zhang T ,Guo J , et al. Janus electrospun fiber membrane based on hydrophilic modified poly (butylene adipate-co-terephthalate) for enhanced meat preservation via dual function synergistic disinfection [J]. Materials Today Chemistry, 2025, 45 102665-102665. DOI:10.1016/J.MTCHEM.2025.102665.

[13]Pang Z H ,Jin G X ,Wang J , et al. High temperature resistant polyamide thin film composite nanofiltration membrane based on polyethylene substrate [J]. Journal of Membrane Science, 2025, 721 123811-123811. DOI:10.1016/J.MEMSCI.2025.123811.

[14]Ma J ,Zhen L ,Yao H , et al. Tunable hydrophilic modification of polyethylene terephthalate membrane via layer-by-layer polyethylenimine grafting [J]. Reactive and Functional Polymers, 2025, 208 106151-106151. DOI:10.1016/J.REACTFUNCTPOLYM.2025.106151.

[15]Chen Y ,Liu X ,Wang W , et al. Crosslinking mineralized interlayer engineering of in situ self-cleaning nanofiltration membranes based on polyethylene substrates [J]. Chemical Engineering Journal, 2025, 504 158926-158926. DOI:10.1016/J.CEJ.2024.158926.

[16]Liu Q ,Li Z ,Lu T , et al. High‐Density Polyethylene Janus Fibrous Membrane with Enhanced Breathability and Moisture Permeability via PDA Assisted Hydrophilic Modification [J]. Macromolecular Rapid Communications, 2025, 46 (11): 2400854-2400854. DOI:10.1002/MARC.202400854.
[17]Wardani K A ,Ariono D ,Subagjo , et al. Hydrophilic modification of polypropylene ultrafiltration membrane by air‐assisted polydopamine coating [J]. Polymers for Advanced Technologies, 2019, 30 (4): 1148-1155. DOI:10.1002/pat.4549.
[18]Fei W Y ,Ma J ,Sun S , et al. Surface Hydrophilic Modification of Polypropylene Fiber by Hydrolysis of Silane Coupling Agent [J]. Key Engineering Materials, 2018, 4628 80-85. DOI:10.4028/www.scientific.net/KEM.779.80.
[19]Haiming S ,Hongwei Y ,Lijing Z , et al. Durable hydrophilic surface modification for PTFE hollow fiber membranes [J]. Reactive and Functional Polymers, 2016, 114 110-117. DOI:10.1016/j.reactfunctpolym.2017.03.010.
[20]Liang C ,Hu C ,Yan K , et al. Hydrophilic nonwovens by Forcespinning™ of isotactic polypropylene blended with amphiphilic surfactants [J]. Fibers and Polymers, 2016, 17 (10): 1646-1656. DOI:10.1007/s12221-016-6339-5.
[21]Huang ,Bin ,Chen , et al. Modification of Hydrophilic Property of Polypropylene Fiber Film with Water-Soluble Chitosan for Improvement of Blood Compatibility [J]. Advanced Science Letters, 2012, 7 (1): 16-20(5). DOI:10.1166/asl.2012.2134.
[22]Hydrophilic Modification of Polypropylene Hollow Fiber Membrane by Dip Coating, UV Irradiation and Plasma Treatment [J]. Korean Membrane Journal, 2005, 7 (1): 19-27.