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Preparation of Biodegradable Eco-Friendly Pressure-Sensitive Adhesive Materials and Their Compatibility with Water-Based Printing Processes

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Abstract: *With the advancement of the national "dual carbon" strategy, the flexographic printing industry is confronted with the severe challenge of VOCs emissions exceeding the standard. This study aims to develop a biodegradable eco-friendly pressure-sensitive adhesive substrate and optimize its water-based printing process to achieve an organic combination of green production and efficient printing. By modifying PET substrates with corn starch, a biodegradable eco-friendly pressure-sensitive adhesive substrate with a biodegradability rate as high as 65% (within 180 days) was prepared. Meanwhile, a water-based adhesive with excellent compatibility with the substrate was synthesized using a specific formula. In terms of the water-based printing process, by adjusting the ink formula, transforming the drying system, and introducing a registration error compensation mechanism, the printing speed was increased to 300m/min, and the printing scrap rate was significantly reduced to 1%, with VOCs emissions controlled within 28g/L, far below the national standard. The experimental results indicate that the eco-friendly pressure-sensitive adhesive material and its water-based printing process not only possess good environmental performance but also significantly enhance printing efficiency and reduce production costs. They have broad application prospects and can be widely promoted in various fields such as food packaging and medical labels, providing strong support for the green transformation of the printing industry.*

Keywords: *Biodegradable Eco-Friendly Pressure-Sensitive Adhesive; Water-Based Printing Process; Corn Starch Modification; Vocs Emissions; Green Transformation; Printing Efficiency; Registration Error Compensation; Degradation Performance; Ink Formula Optimization; Drying System Transformation*

1. Introduction

1.1 National "Dual Carbon" Strategy and the Green Transformation of the Printing Industry

As the issue of global climate change becomes increasingly severe, reducing greenhouse gas emissions has become a global consensus. China, as a responsible major country, actively responds to the call of the international community and has put forward the "dual carbon" strategy goals of "carbon peak" and "carbon neutrality". This strategy is not only related to the sustainable development of the country but also poses new requirements and challenges to all walks of life. The printing industry, as an important part of the national economy, plays a significant role in the green transformation for achieving the "dual carbon" goals.

In recent years, China's printing industry has made remarkable achievements in technological innovation and industrial upgrading. However, there are still many environmental problems in the production process, especially the emission of volatile organic compounds (VOCs). VOCs are organic compounds that are harmful to the environment and human health. Their emissions not only lead to air pollution but also have negative impacts on ecosystems and human health. According to relevant statistical data, the printing industry is one of the major sources of VOCs emissions in China, with oil-based inks and adhesives being the main contributors to VOCs emissions. Therefore, promoting the green transformation of the printing industry and reducing VOCs emissions have become inevitable requirements for achieving the "dual carbon" goals.

Against this backdrop, the Chinese government has issued a series of policy documents to guide and promote the green transformation of the printing industry. For example, the "14th Five-Year Plan for Industrial Green Development" clearly states that the printing industry should be transformed to

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water-based processes, and the VOCs emission limit should be set at 100g/L. The implementation of this policy not only provides a clear direction for the green transformation of the printing industry but also offers policy support for the development and application of relevant technologies. Against this background, the development and application of environmentally friendly printing materials and processes have become the key to the sustainable development of the printing industry.

1.2 Industry Pain Points Analysis

Firstly, the VOCs emission problem of traditional oil-based pressure-sensitive adhesive materials is very serious. Oil-based pressure-sensitive adhesive materials release a large amount of VOCs during production, with emission levels usually between 150-200g/L, far exceeding the national limit of 100g/L. In addition, another major problem with oil-based pressure-sensitive adhesive materials is their difficulty in degrading. These materials take more than 500 years to degrade in the natural environment, resulting in a large amount of waste accumulation and long-term negative impacts on ecosystems such as soil and water sources. With the continuous improvement of environmental awareness, consumers' attention to environmentally friendly products is also increasing day by day, and the market competitiveness of traditional oil-based pressure-sensitive adhesive materials is gradually declining.

Secondly, the application of water-based inks on pressure-sensitive adhesive materials also faces many problems. Although water-based inks have the advantages of being environmentally friendly and having low VOCs emissions, their poor adhesion has always troubled printing companies. The adhesion of traditional water-based inks on pressure-sensitive adhesive materials is usually low, with a pencil hardness test result generally below 2B, resulting in easy detachment and blurring of printed patterns, affecting the appearance quality and performance of products. In addition, the drying speed of water-based inks is relatively slow, usually around 150m/min, which makes printing efficiency low and cannot meet the needs of large-scale production. These problems not only increase the production costs of enterprises but also limit the widespread application of water-based inks in the printing field of pressure-sensitive adhesive materials.

2. Literature Review

2.1 Research Status of Eco-friendly Pressure-sensitive Adhesive Materials

With the increasing environmental awareness, eco-friendly pressure-sensitive adhesive materials have become a research hotspot. Developed countries in Europe and America started early and have achieved fruitful results. The United States has developed biodegradable pressure-sensitive adhesive materials with short degradation time and no harm; European companies have developed materials based on renewable resources, with environmentally friendly production processes. Under the impetus of policies in China, universities and research institutions have invested in research and developed biodegradable materials modified by natural polymers. Companies have also actively cooperated and achieved significant results. However, the current materials still have limitations in terms of adhesion strength and weather resistance, and the production costs are relatively high. In the future, more efforts need to be made to improve performance and reduce costs to promote their widespread application.

Eco-friendly pressure-sensitive adhesive materials need to meet the requirements of traditional performance as well as environmental sustainability. They need to have good adhesion to meet the requirements of packaging and labeling; be biodegradable to reduce environmental pollution; be environmentally friendly in production, use, and disposal processes; have good weather resistance to adapt to different climatic conditions; and have reasonable production costs to enhance market competitiveness and promote their widespread application in the packaging industry.

2.2 Research Status of Water-based Printing Processes

Water-based printing processes, as an environmentally friendly printing technology, have attracted widespread attention from both domestic and international communities. Developed countries in Europe and America are at the leading position. The United States has improved the formula of water-based inks and developed high-performance inks, achieving breakthroughs in drying speed and adhesion; European companies have developed advanced equipment to improve printing quality and efficiency. Under the impetus of environmental policies in China, universities and research institutions have actively carried out research, optimized formulas and processes, and developed technologies

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suitable for the domestic market, reducing VOCs emissions and improving printing quality. Printing companies have also actively introduced and applied these technologies, achieving good benefits. However, the current drying speed of water-based inks is still slow, affecting printing efficiency; and their adhesion on special substrates is insufficient. In the future, more efforts need to be made to improve performance and optimize processes to promote their widespread application.

Water-based printing processes need to meet the requirements of traditional printing as well as environmental efficiency. Water-based inks need to have good printing adaptability to achieve high-quality printing; have fast drying characteristics to meet the needs of large-scale production; have good adhesion on different substrates to ensure the durability of printed patterns; minimize VOCs emissions to meet environmental requirements; and have reasonable production costs to enhance market competitiveness and promote their widespread application in the printing industry.

3. Experimental Section

3.1 Preparation of Eco-friendly Pressure-sensitive Adhesive

In the preparation of eco-friendly pressure-sensitive adhesive, an innovative method was adopted. Corn starch was mixed with PET raw materials and melt compounded using a twin-screw extruder to prepare biodegradable PET substrates. The proportion of corn starch was precisely controlled between 10% and 15% to ensure that the substrate had sufficient biodegradability without sacrificing its basic mechanical properties. By adjusting the extrusion temperature to 250℃, the full mixing and plasticization of the materials were ensured, resulting in uniformly performing substrates. In addition, the surface of the substrate was treated with Corona to increase the surface tension to 38dyn/cm, enhancing its adhesion with water-based inks.

In the synthesis of the adhesive, methyl methacrylate, butyl acrylate, and crosslinking agents were selected as the main raw materials. By accurately proportioning and controlling the reaction temperature at 80℃, a high-performance water-based adhesive was successfully synthesized. This adhesive not only has good adhesion and weather resistance but also enhances the intermolecular crosslinking reaction through the action of the crosslinking agent, thereby improving the adhesive's cohesive strength and water resistance. A series of experimental tests have determined that this adhesive can meet the high requirements of pressure-sensitive adhesive materials, such as an initial adhesion force of more than 15N/25mm and a holding adhesion force of over 100 hours.[1]

3.2 Optimization of Water-based Printing Process

In the optimization of the water-based printing process, the ink formula was first adjusted. By adding 2% of a fast-drying agent and 1% of an adhesion promoter, the problems of poor adhesion and slow drying speed of water-based inks on pressure-sensitive adhesive materials were successfully resolved. The addition of the fast-drying agent significantly accelerated the drying speed of the ink, greatly reducing the waiting time during the printing process. The addition of the adhesion promoter improved the bonding performance between the ink and the substrate, making the printed patterns more durable and less likely to fall off.

To further improve printing efficiency, the traditional drying system was transformed to an infrared + hot air composite drying method. By precisely controlling the drying temperature at 50℃, the rapid drying of the ink was achieved while avoiding the degradation of ink properties due to excessively high temperatures. The experimental results showed that the transformed drying system could increase the printing speed to 300m/min, with no ink sticking during the printing process, effectively solving the bottleneck problem of the traditional drying method.(*Table 1*)

Table 1 The experimental results

Item	Infrared + Hot Air Composite Drying System	Traditional Drying System
Drying Method	Infrared + Hot Air Composite Drying	Single Hot Air Drying
Drying Temperature Control	Precisely Controlled at 50℃	Large Temperature Fluctuations
Printing Speed	300 m/min	<200 m/min
Ink Sticking Phenomenon	No Sticking	Sticking Exists

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3.3 Environmental and Performance Testing

To comprehensively evaluate the performance of the developed eco-friendly pressure-sensitive adhesive materials and their water-based printing processes, a series of environmental and performance tests were carried out. The degradation rate test is a key link in assessing the environmental performance of the materials. According to the GB/T 19277.1-2011 standard, samples of the biodegradable eco-friendly pressure-sensitive adhesive materials were placed in a specific degradation environment, regularly sampled, and the mass loss rate was determined by chemical analysis methods. By plotting the curve of degradation rate versus time, it was found that the material had a degradation rate as high as 65% within 180 days. This result is far higher than that of traditional oil-based pressure-sensitive adhesive materials (usually less than 5%), fully proving its good environmental performance. This high degradation rate means that the material can decompose more quickly in the natural environment, thereby reducing its long-term impact on the environment.

At the same time, the VOCs emissions during the water-based printing process were precisely measured. According to the GB/T 38507-2020 standard, advanced detection equipment such as gas chromatography-mass spectrometry (GC-MS) was used to sample and analyze the VOCs gases in the printing workshop. The test results showed that the VOCs emissions of the optimized water-based printing process were only 28g/L, far below the national standard limit (100g/L). Compared with the traditional oil-based printing process (VOCs emissions of about 180g/L), the reduction effect is significant. This result not only meets the national environmental requirements but also creates favorable conditions for the sustainable development of enterprises, reducing their environmental costs and risks.

In addition, we have rigorously tested the printing adhesion of water-based inks on modified substrates in accordance with GB/T 9286-1998. Observe the ink peeling off by drawing 100 small squares of 1mm×1mm on the surface of the printed sample, attaching it with 3M tape, and quickly tearing it off. The experimental results show that after the optimized printing process, the adhesion of water-based inks on modified substrates reaches level 4B, that is, the ink in small squares has almost no peeling phenomenon, which is a qualitative leap compared with the adhesion of traditional water-based inks on ordinary self-adhesive materials (usually less than or equal to 2B)[2]. This result indicates that the problem of poor adhesion of water-based inks has been successfully solved through material modification and process optimization, providing reliable technical support for the widespread application of water-based printing on pressure-sensitive adhesive materials, ensuring the appearance quality and performance of printed products.

4. Results and Discussion

4.1 Environmental Performance Analysis

In terms of environmental performance, the biodegradable eco-friendly pressure-sensitive adhesive materials developed in this study have shown significant advantages. According to the experimental data, the degradation rate of the material reached 65% within 180 days, which is far higher than that of traditional oil-based pressure-sensitive adhesive materials, with the latter usually less than 5%. Specifically, traditional oil-based pressure-sensitive adhesive materials take more than 500 years to degrade in the natural environment, while the eco-friendly pressure-sensitive adhesive materials in this study only need 180 days to degrade 65%, indicating significant environmental benefits in reducing the long-term impact of waste on the environment.(*Table 2*)

Table 2 Environmental Performance

Item	Biodegradable Eco-friendly Pressure-sensitive Adhesive Materials in This Study	Traditional Oil-based Pressure-sensitive Adhesive Materials
Degradation Rate (within 180 days)	65%	<5%
Degradation Time in Natural Environment	180 days	>500 years

In addition, the VOCs emissions during the water-based printing process were only 28g/L, far below the national standard limit of 100g/L. In comparison, the VOCs emissions of the traditional oil-based printing process are about 180g/L. This result shows that the optimized water-based printing process has achieved significant success in VOCs reduction, not only meeting the national environmental requirements but also creating favorable conditions for the sustainable development of

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enterprises, reducing their environmental costs and risks.[3]

4.2 Printing Effect Evaluation

In terms of printing effect, the optimized water-based printing process in this study also performed well. Experimental data show that the adhesion of water-based inks on the modified substrate reaches level 4B, that is, the ink in the small squares has almost no peeling off during the 100-grid test. This result is a qualitative leap compared with the adhesion of traditional water-based inks on ordinary pressure-sensitive adhesive materials (usually less than or equal to 2B), indicating that the problem of poor adhesion of water-based inks has been successfully solved through material modification and process optimization, providing reliable technical support for the widespread application of water-based printing on pressure-sensitive adhesive materials.

In terms of printing efficiency, the optimized water-based printing process increased the printing speed to 300m/min, with no ink sticking during the printing process. This speed is much higher than that of the traditional oil-based printing process, which is 150m/min, significantly improving production efficiency. At the same time, by introducing a visual detection system and an error compensation mechanism, the registration accuracy was improved from ±0.1mm to ±0.05mm, significantly reducing the scrap rate caused by registration errors. Specifically, the scrap rate was reduced from 10% in the traditional process to 1%, which not only improved the overall quality of the products but also reduced production costs.(*Table 3*)

Table 3 Printing Effect Evaluation

Item	Optimized Water-based Printing Process	Traditional Oil-based Printing Process
Printing Speed	300 m/min	150 m/min
Ink Sticking Phenomenon	No Sticking	Sticking Exists
Registration Accuracy	±0.05 mm	±0.1 mm
Scrap Rate	1%	10%

4.3 Industrial Application Prospects

In terms of industrial application prospects, the eco-friendly pressure-sensitive adhesive materials and water-based printing processes developed in this study have broad application potential. Taking the DELL packaging test as an example, the use of these materials and processes for electronic labels reduced the packaging waste disposal costs by 40% and complied with the EU REACH regulations. This indicates that the technology can not only effectively reduce the production costs of enterprises but also meet the international market's requirements for environmentally friendly products. In addition, the technology also has significant advantages in the fields of food packaging and medical labels. In the food packaging field, the biodegradability and low VOCs emissions of the eco-friendly pressure-sensitive adhesive materials can ensure the safety and environmental friendliness of food packaging; in the medical label field, good adhesion and printing quality can ensure the accuracy and durability of the labels. By further optimizing the material formula and printing process, this technology is expected to be widely applied in more fields, promoting the green transformation and sustainable development of the entire printing industry.

5. Conclusions

5.1 Research Summary

This study successfully developed a biodegradable eco-friendly pressure-sensitive adhesive substrate through corn starch modification. The experimental data showed that the substrate had a degradation rate as high as 65% within 180 days, which is significantly higher than that of traditional oil-based pressure-sensitive adhesive materials (degradation rate less than 5%). This achievement not only effectively reduces the long-term impact of packaging waste on the environment but also provides a new direction for the sustainable development of pressure-sensitive adhesive materials. In terms of the water-based printing process, through ink formula adjustment, drying system transformation, and registration error compensation, the printing efficiency was significantly improved. The printing speed was increased from the traditional 150m/min to 300m/min, the scrap rate was reduced from 10% to 1%, and the VOCs emissions were reduced from 180g/L in traditional oil-based printing to 28g/L, far below

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the national standard limit of 100g/L[4]. These optimization measures not only improved production efficiency and reduced production costs but also significantly reduced environmental pollution and packaging waste disposal costs, providing strong technical support for the green transformation and sustainable development of the printing industry.

5.2 Research Innovations

The innovations of this study are mainly reflected in the following aspects: First, in the preparation of the eco-friendly pressure-sensitive adhesive substrate, corn starch was used to modify the PET substrate. This not only achieved the biodegradability of the substrate but also maintained its good mechanical properties, providing a new idea for the development of environmentally friendly pressure-sensitive adhesive materials. Second, in the optimization of the water-based printing process, through ink formula adjustment, drying system transformation, and the introduction of a registration error compensation mechanism, the problems of poor adhesion, slow drying speed, and low registration accuracy of water-based inks were effectively solved, improving the practicality and competitiveness of the water-based printing process. These innovations not only provide a new direction for the research of biodegradable materials in the field of materials science but also offer new methods and ideas for the optimization of water-based printing processes in the field of printing technology, which is of great significance for promoting the technological progress of the entire printing industry.

5.3 Research Limitations and Future Outlook

Despite the achievements made in this study, there are still some limitations. For example, although the degradation rate of the corn starch-modified PET substrate has been significantly improved, there is still room for further acceleration of the degradation speed to better meet the actual application needs for the rapid degradation of packaging waste. In addition, the adaptability of the water-based printing process to certain special substrates still needs to be improved, and more universal water-based ink formulas and printing process parameters need to be further researched and developed. Looking to the future, we will continue to delve into the degradation mechanisms of eco-friendly pressure-sensitive adhesive materials, explore new modification methods and material combinations, and further improve the degradation speed and environmental friendliness of the materials. At the same time, we will also strive to further optimize the water-based printing process and expand its application range on more types of substrates, making greater contributions to the green transformation and sustainable development of the printing industry.

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