The Effects of Zinc Oxide/Silicon Dioxide Composite Coating on Surface Wettability and the Mechanical Properties of Paper Mulching Film

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Abstract: In order to improve the hydrophobic and mechanical properties of paper mulch film, ZnO/SiO$_2$ composite coated paper mulch film was prepared with a brush coating method. Hydrotropicity and durability of the original paper mulch film and the coated paper mulch film were measured by static contact angle and mechanical torsion tests, and the mechanical properties of the two kinds of paper mulch films were measured by tensile and tear tests at different temperatures. The two kinds of paper mulch films were characterized by their micro-morphology and surface element distribution. The results show that the contact angle of the ZnO/SiO$_2$ composite coated paper mulch film reaches 161.46°, and the contact angle can still reach 153.15° after 80 mechanical torsion cycles, which shows good superhydrophobic and hydrophobic durability. Compared with the original paper mulch film, the mechanical properties of the coated paper mulch film are also improved to some extent. Combined with the surface micro-morphology, it is found that a ZnO/SiO$_2$ composite coating fills the pores between fibers in the paper mulch film and promotes the adhesion between fibers, thus improving the hydrophobicity, durability, and mechanical properties of the paper mulch film.

Keywords: paper mulching film; zinc oxide; silicon dioxide; superhydrophobic; hydrophobic durability; mechanical properties

1. Introduction

It has been about 70 years since plastics were used in agriculture (such as plastic greenhouses, plastic mulching films, irrigation plastic water pipes, etc.). With the increase in economic benefits, the demand for plastics in agriculture is increasing, and the non-degradation of plastics brings huge problems to society and the environment [1,2]. In order to protect the environment in which human beings live, scholars at home and abroad are vigorously studying and popularizing degradable paper mulching film [3–5], and agricultural paper mulching film technology has demonstrated remarkable effects in expanding the planting area of crops, increasing the yield of crops, and coping with natural disasters [6–9].

Because the paper-based film is often affected by rainfall during the covering and general use process, its performance will decrease when it encounters water. A superhydrophobic paper-based film can be prepared to effectively avoid the influence of rainfall on the performance of the paper-based film. At present, the preparation technology of superhydrophobic surfaces mainly includes the soaking method, spraying method, vapor deposition method, and template method [10]. Baidya et al. [11] prepared a superhydrophobic paper with cellulose nanofibers as a matrix after fluorination treatment, and the results showed that the hydrophobic paper had good hydrophobic and mechanical properties. Cappelletto et al. [12] prepared a silicone coating on a paper surface with the sol–gel method...
to obtain a superhydrophobic surface. The results show that the higher the methyl number of the silicone precursor in the coating, the stronger the hydrophobicity of the coating. Kang et al. [13] treated kraft paper and paperboard with a nano-SiO$_2$ hydrophobic coating and found that SiO$_2$ improved the hydrophobic properties of paper and paperboard to a certain extent, and also improved the physical properties of paper and paperboard to a certain extent. Sanjay et al. [14] deposited SiO$_2$ and polystyrene composite materials on a rattan leaf net by a simple deposition method to obtain a micro-coarse structure, and finally obtained a superhydrophobic leaf net, and its oil–water separation effect and hydrophobic performance were better than those of a traditional Cu net superhydrophobic surface. Wang et al. [15] used an in situ hydrolysis method to hydrolyze tetraethyl titanate and combine it with paper fibers to obtain a superhydrophobic surface, and the morphology of the surface microstructure can be controlled by adjusting the content of acetic acid.

The mechanical properties of paper mulch film will decrease due to the climate and other factors when in use. Therefore, the research on improving the mechanical properties of paper and paper mulch film is very extensive. Yang et al. [16] modified a paper’s surface by multi-layer deposition polymerization of polydimethyl ammonium chloride and silica particles and obtained paper with high tensile strength and pollution resistance. Musikavanhu et al. [17] activated the fibers to make the silica coating adhere to them more closely, thus improving the mechanical strength and durability of paper. Yu et al. [18] filled “sticky” mineral particles into the fiber network of paper, which improved the support of the paper base and created strong adhesion to water. Wang et al. [19] realized paper coating with micro-nano delamination, and the treated paper showed excellent mechanical durability under 100 times deformation and had remarkable stability to both acidic and alkaline solutions. Affected by raw film material cost, material cost, and popularization and application, agricultural mulch film still uses plant fiber or starch as its basic raw materials, and paper mulch film adopts a conventional papermaking process, which is then processed, therefore, the paper produced often does not fully meet the mechanical properties, mechanical durability, and mechanical strength at different temperatures that are required by agricultural paper mulch film [20,21].

In this study, zinc oxide solution with a certain concentration and silicon dioxide were uniformly brushed on the surface of paper mulch film, and the paper mulch film was modified at different levels. The zinc oxide coating filled and bonded the pores between the fibers of the paper mulch film, and the silicon dioxide coating made the paper mulch film obtain superhydrophobic performance by constructing a micro-rough structure on the surface of the paper mulch film. The hydrophobic and mechanical properties of the paper mulch film were improved by this composite coating modification.

2. Experimental Part

2.1. Main Experimental Raw Materials

The fully degradable paper-based film was obtained from Shandong Rebos Tobacco Co., Ltd., Shandong, China, the nano-SiO$_2$ with model HB-139 was purchased from Yichang Huifu Silicon Material Co., Ltd., Hubei, China, the absolute ethanol with analytical purity of 95% was provided by Fuyu Chemical Co., Ltd., Dongying, China, the ZnO with model DXH-LH30Y was obtained from Darcy Nano Technology Co., Ltd., Jiangsu, China, and the deionized water used in the experiment was made by the laboratory.

2.2. Sample Preparation

A total of 4 g of zinc oxide powder and silicon dioxide powder were added, respectively, into 100 mL of absolute ethanol solution and ultrasonically vibrated for 15 min to obtain zinc oxide dispersion and silicon dioxide dispersion, respectively. Firstly, the zinc oxide dispersion liquid was uniformly brushed on the surface of the paper mulching film with a brush, the brushed paper mulching film was put into a drying box at a temperature of 60 °C for drying for 5 min, and then the dried paper mulching film was taken out, then the silica dispersion on the surface of the dried paper mulching film was evenly brushed
with a brush, then put into a drying box at 60 °C for 5 min, and finally, the prepared ZnO/SiO$_2$ composite coated paper mulching film was taken out, as shown in Figure 1.

![Figure 1. Preparation process of plastic film sample of ZnO/SiO$_2$ composite coated paper.](image)

2.3. Performance Test of Samples

The surface of the sample was characterized with SU8020 field emission scanning electron microscope (Hitachi, Hitachi, Japan). The contact angle of samples was measured by HKCA-15 contact angle tester (Beijing Hacker Instrument Factory, Beijing, China). The WDW-10 M microcomputer controlled electronic universal testing machine (Jinan Zhongluchang Testing Machine Manufacturing Co., Ltd., Jinan, China) was used to carry out tensile and tear tests of samples at different temperatures. The running speed of the testing machine was 100 mm/min, and each group of samples was tested 5 times to take the average value. In the high and low temperature test, SX2–4-10 box resistance furnace (Bangxi Instrument Technology Co., Ltd., Shanghai, China) and DW-40 low temperature test chamber (Cangzhou Huayi Test Instrument Co., Ltd., Cangzhou, China) were used to treat the samples at high and low temperatures. During the test, a high temperature infrared imager was used to control the temperature of the sample.

3. Results and Discussion

3.1. Morphology and Characterization of Particles

By observing Figure 2a,b, we can clearly see the difference in surface structure between silicon dioxide and zinc oxide. Silicon dioxide has an irregular sheet structure, while zinc oxide has an irregular baseball shape. Silicon dioxide has randomly distributed flaky particles, which do not easily form an agglomeration, while zinc oxide has baseball-like particles with different sizes and irregular shapes, with an average size of 70.8 nm. Ultrafine particles are easy to combine with polymer materials and have good dispersibility. Considering the structural differences between the two kinds of particles, a relatively large gap is formed between the fibers of the paper mulching film, so the irregular baseball-like zinc oxide coating is firstly brushed, which means it is uniformly dispersed in the paper mulching film and penetrates into the paper mulching film material through the pores to achieve the functions of filling and adhesion. This is more conducive to the combining of fibers and improves the mechanical properties of the paper mulching film. Then, brush-coating silicon dioxide with its flaky structure fills the fiber pores that were not completely
filled by zinc oxide, which plays the role of surface hydrophobic structure construction, 
finally obtaining a ZnO/SiO2 composite coating with a micro-rough structure.

![Figure 2. (a) Electron micrograph of silicon dioxide, (b) Electron micrograph of zinc oxide.](image)

3.2. Micro-Morphology Analysis of the Paper Mulching Film

Figure 3 shows the surface topography of the base paper mulching film and the coated paper mulching film, respectively. It can be seen from Figure 3a,d that the overall shape of the fibers in Figure 3a is clear, and the fibers are obviously exposed to the outside, with an uneven surface and many pores, while the gap between the fibers in Figure 3d is filled by two kinds of particles and the surface morphology is rough. It can be clearly seen from b, c, e, and f in Figure 3 that the surfaces of the fibers in Figure 3b,c are smooth, and from Figure 3c, there is almost no adhesion between the fibers, more pores, fewer burrs on a single fiber, and more fibers in Figure 3e,f. It can be seen from Figure 3f that the surface of a single fiber is uniformly covered by the coating and the gaps between the fibers are uniformly filled by the coating, which shows that the fibers forming the paper mulch film are initially irregularly arranged and that the coating then plays the role of filling and adhesion so that the cracks between the fibers are filled and the potholes and pores on the surface are reduced.

According to the observation and analysis of the EDS elements on the surface of the original paper mulching film in Figure 4a–d, the main elements of the original paper mulching film are the c element, n element, and o element. According to the observation and analysis of the EDS elements on the surface of the coated paper mulching film in Figure 4e–j, the main elements of the coated paper mulching film have two kinds more than those of the original paper mulching film, namely Zn and Si, and the percentage contents of C and O in the coated paper mulching film is reduced by 25.9% and 14.2%, respectively, compared with the original paper mulching film. The reason for this is that the Zn and Si elements are added into the coated paper mulch film, and the percentages of the Zn and Si elements are 9.8% and 30.5%, respectively, indicating that the Zn and Si elements are contained in the coating film. By comparing the percentage distribution of the elements between the coated paper mulch film and the original paper mulch film, the distribution of the EDS elements on the surface of coated paper mulch film is more uniform than that of the original paper mulch film, and the percentage of each element is more balanced.
The weight of the original paper mulch film decreased from 100% to about 19%, with a total loss of water vapor [22]. After 150 °C was the weight loss caused by the volatilization of water adsorbed on paper fibers, while produced by the pyrolysis of cellulose, and the weight loss was most obvious at this stage.

Figure 3. (a) SEM images of base paper mulching film surface, (b) SEM images of base paper mulching film fiber, (c) SEM images of base paper mulching film fiber, (d) SEM images of coated paper mulching film surface, (e) SEM images of coated paper mulching film fiber, (f) SEM images of coated paper mulching film fiber.

Figure 4. (a) EDS diagram of base paper mulching film surface, (b) Distribution map of C element in base paper mulching film, (c) Distribution map of N element in base paper mulching film, (d) Distribution map of O element in base paper mulching film, (e) EDS diagram of coated paper mulching film surface, (f) C element distribution map of coated paper mulching film, (g) N element distribution map of coated paper mulching film, (h) O element distribution map of coated paper mulching film, (i) Zn element distribution map of coated paper mulching film, (j) Si element distribution map of coated paper mulching film.

The two curves in the thermogravimetric graph in Figure 5 show the weight loss of the original paper mulching film and the coated paper mulching film when heated continuously from 30 to 1000 °C. It can be seen from the Figure that before 150 °C, the weight loss of the original paper mulch film accounts for about 3% of the total mass, which was the weight loss caused by the volatilization of water adsorbed on paper fibers, while the weight loss of the coated paper mulch film is 1.6%, which showed that the modification improved the superhydrophobic of the mulch film and hindered the adsorption of the water vapor [22]. After 150 °C, in the temperature range of 238–492 °C, the weight loss at this stage was caused by the small molecular gas and macromolecular volatile substances produced by the pyrolysis of cellulose, and the weight loss was most obvious at this stage. The weight loss of the original paper mulching film accounts for about 75% of the total mass, while that of the coated paper mulching film was 71%, indicating that the coated paper mulching film has better thermal stability. The weight loss after 638–699 °C was mainly due to the carbon oxidative decomposition of cellulose, and the weight loss of the two kinds of paper was about 2% of the total mass. During the whole heating process, the weight of the original paper mulch film decreased from 100% to about 19%, with a total loss
of about 81%. Under the same conditions, the final weight of the coated paper mulch film after pyrolysis was about 25%, which was 6% more than that of the original paper mulch film. The extra weight of the coated paper mulch film was caused by the particle coating on the paper's surface. Therefore the results of thermogravimetry also proved that the particles were successfully coated on the surface of the paper mulch film, thus successfully modifying the paper and obtaining a coated paper mulch film.

![Thermogravimetric chart](image)

**Figure 5.** Thermogravimetric chart.

Figure 6 shows the element penetration between two points of the thickness and profile of coated paper mulch film. According to the illustration’s observation and analysis in Figure 6a,c, the surface of the coating contacting with the outside is relatively flat, while the surface of the coating contacting with the fibers is uneven, and part of the coating has penetrated into the paper mulching film through the cracks between the fibers, indicating that the original paper mulching film with an uneven surface and cracks was relatively flat after being brushed by the composite coating, and the gaps between the fibers were also filled by the coating.

According to the observation and analysis of Figure 6b,c, the Zn content and Si content at points A and B were almost the same, while the Si content was the highest at a distance of 20 µm from point A, seen from the thickness of Figure 6a, the thickness of the coating was about 11 µm. According to the trend of the element permeation curve in Figure 6b, the Si element diffuses through the zinc oxide coating from the outside to the inside and diffuses rapidly. When it reaches the fiber layer, the element diffusion is slow and the element retention phenomenon is serious [23], which shows that zinc oxide coating covers the fiber well, fills the fiber gap and crack sufficiently, and the Si element permeates evenly from 20 µm away from point A.
According to the trend of the element permeability curve in Figure 6b, Zn was mainly concentrated in the interval about 40 μm away from point A. The Zn element is different from the Si element due to its one-way diffusion mode. The Zn element diffuses bidirectionally, spreading to the silica coating while also spreading to the fiber layer. The Zn element diffuses through the silica coating from the inside to the outside, and the diffusion is slow because the process of preparing the composite coated paper mulch film means first brushing it with zinc oxide, then drying it, then brushing it with silica so that the solid zinc oxide coating comes into contact with the silica solution, and the solid zinc oxide is dissolved in the silica solution first. When spreading to the fiber layer, the Zn element diffuses quickly because there are many pores and cracks on the fiber surface. When brushing, zinc oxide solution permeates through the pores and cracks, and the Zn element does not appear to create an obvious retention phenomenon.

### 3.3. Analysis of the Hydrophobic Stability of the Paper Mulching Film

Figure 7 shows the mechanical bending and mechanical twisting diagram of the paper mulching film, and the mechanical process repeats in b–e in Figure 7, respectively, measuring the contact angle of each group of samples before the test. By observing Figure 8a and its illustrations, the contact angle of the original paper mulching film was 131.53° ± 1.50°, and that of the coated paper mulching film was 161.46° ± 1.50°. Combined with the surface micro-morphology of the paper mulch film, this shows that the ZnO/SiO2 composite coating builds a micro-rough structure on the surface of paper mulch film, which makes the surface obtain superhydrophobic properties.

Figure 8 is a comparison diagram of the contact angles between the original paper mulching film and the coated paper mulching film and a contact angle diagram corresponding to the mechanical bending cycle times of the coated paper mulching film. By observing and analyzing the contact angle data in Figure 8b, mechanical bending and mechanical twisting cycle steps b–e in Figure 7, a set of contact angle data was measured every 20 times for comparative analysis. With the increase in mechanical bending and mechanical twisting cycles, the contact angle degree of coated paper mulch film decreased, but it still kept good hydrophobic properties.
Figure 7. (a) Sample diagram before mechanical property test, (b) Upward bending diagram, (c) Downward bending diagram, (d) Left-side upward twisting diagram, (e) Right-side upward twisting diagram.

Figure 8. (a) Comparison diagram of contact angle between original paper mulch film and coated paper mulching film, (b) Contact angle diagram corresponding to mechanical bending cycle times.

Figure 8 is the contact angle comparison chart of the original paper mulch film and the coated paper mulch film and the contact angle map corresponding to the number of mechanical bending cycles of the coated paper mulch film. By observing and analyzing the contact angle data in Figure 8b, mechanical bending and mechanical distortion steps b–e in Figure 7 are cycled. Each time the mechanical bending and mechanical twisting interval achieves 20 cycles, the sample was taken out to measure a set of contact angle data for comparative analysis. As the number of mechanical bending and mechanical twisting cycles increased, the contact angle of the coated paper mulch decreased, but it still maintained good hydrophobic properties.
Figure 9 is a comparison chart of acid, alkali, and salt corrosion resistance between the original paper mulching film and the coated paper mulching film. The time corresponding to b–d in Figure 9 is continuous and uninterrupted at 22:00, 06:00, and 10:00, respectively. According to the corrosion situation in the Figure, the original paper mulch film is obviously less corrosion-resistant than the coated paper mulch film. The acid solution of the original paper mulch film penetrated most obviously after 8 h, and the salt solution also partially crystallized, while the alkali solution and the aqueous solution did not penetrate as obviously. It was found that the four solutions had no obvious penetration by observing the coated paper mulch film. From Figure 9c to d at 4 h, it was found that the four solutions on the original paper mulch film and the coated paper mulch film had all penetrated and volatilized, some of them being due to environmental factors, which is also in line with reality. In reality, the paper mulch film would be used all day and night. According to the phenomenon in Figure 9d, it could be seen that the penetration ring of the red alkaline solution was large, which indicated that the original paper mulch film had poor alkali resistance, while the penetration ring of the red alkaline solution on the surface of the coated paper mulch film was almost absent, and the penetration ring of the blue acidic solution was obvious, indicating that the coated paper mulch film had poor performance in an acid-resistant solution [24]. The acid solution permeated the ZnO coating through the SiO2 coating, and ZnO is an alkaline substance, which reacts with an acid solution, thus reducing the coating coverage and allowing the solution to permeate and corrode the fibers. Therefore, the acid resistance of the coated paper mulch film is slightly inferior to alkali resistance, but the ZnO/SiO2 composite coating plays a covering and blocking role in the paper mulch film corrosion resistance test, which improved the corrosion resistance of the paper mulch film.

**Figure 9.** (a) Schematic diagram of acid, alkali, and salt, (b) Comparison diagram of 0 h corrosion resistance between base paper mulching film and coated paper mulching film, (c) Comparison diagram of 8 h corrosion resistance between base paper mulching film and coated paper mulching film, (d) Comparison diagram of 12 h corrosion resistance between base paper mulching film and coated paper mulching film.

3.4. Analysis of the Tensile Properties of the Paper Mulching Film

Figure 10 is a drawing of the tensile process, tensile fracture electron microscope, tensile force–displacement graph, and tensile strength diagram. As shown in Figure 10a,
the tensile strength of the coated paper mulch film and the original paper mulch film were 34.21 MPa and 32.79 MPa, respectively. It can be seen that the tensile strength of the coated paper mulch film increased by 4.16% compared with that of the original paper mulch film, indicating that the coating can improve the mechanical properties of the paper mulch film to some extent. As shown in Figure 10b, after the paper mulch film was pulled by the tensile testing machine, the burrs at the fracture surface increased, and the fracture surface was irregular, but there was no large inclination on both sides as a whole, which indicated that the paper mulch film was stressed uniformly when stretched. After the paper mulch film was pulled off, the fibers at the fracture appeared to pull out, and the fibers were interlaced with each other. The fibers were pulled out evenly from one side, which indicated that the stress concentration points of the paper mulch film were reduced or the damage caused by the stress concentration was reduced [25–27]. It can be seen from Figure 10c,d that the tensile strength of the coated paper mulching film was slightly higher than that of the original paper mulching film.

By observing Figure 11a and its illustrations, it can be seen that the fibers of the original paper mulch film were disordered and there were obvious gullies on the surface. By observing Figure 11b, the broken fibers of the paper mulch film were arranged in disorder, and the fibers were interlaced with each other. Paper mulch film is paper with a porous structure, which is made of plant fibers. As the skeleton structure of plants, plant fibers make each plant stand upright in space and have a certain strength. Two factors are that the original paper mulching film can bear external forces which are the strength of a single fiber and the bonding force between the fibers. It can be observed from Figure 11c that when the paper mulch film was tensioned, the short fibers were stressed first, and as
the fibers were gradually elongated, the fine fibers attached to the fiber surface played a wrapping role, as shown in Figure 11f, providing stronger bearing capacity for the fibers, and then the longer fibers were tensioned to provide more bearing capacity. Finally, the fibers in contact with each other were separated, as shown in Figure 11e. When the two fibers were separated, the separation and fuzzing on the fiber surface played a certain binding role. When a single fiber bears the tensile limit, it will break. When all fibers reach the stress limit, the paper mulch sample will break.

![Figure 11](image_url)

**Figure 11.** (a) Macroscopic view of base paper mulch film, (b) Microscopic view of base paper mulch film fracture, (c) Enlarged microscopic view of base paper mulch film fracture, (d) Microscopic view of base paper mulch film fracture fiber, (e) Low magnification electron microscope image of the fractured fibers of the base paper mulch film, (f) Microscopic view of base paper mulch film fracture fiber, (g) Microscopic view of coated paper mulch film fracture, (h) Microscopic view of coated paper mulch film fracture fiber, (i) Enlargement electron microscopy of fiber fracture of coated paper film.

The fiber constituting the paper mulching film itself is a transparent substance, but it can be seen from the observation of Figure 11d that the paper mulching film was bright and uneven because when light shines on the paper mulching film surface, the pores and cracks on the paper mulching film surface produced a diffused reflection of the light, meaning the light cannot pass through, demonstrating an opaque state. At the same time, it also shows that there is a floc between the fibers, which leads to poor surface uniformity of the paper mulching film and uneven stress among the fibers, thus affecting the mechanical properties of the paper mulching film. However, it can be seen from Figure 11g that the surface of the coated paper mulch film is relatively uniform, indicating that the coating was well distributed on the surface of the paper mulch film and therefore improved its mechanical properties.

By observing and analyzing Figure 11h,i, it can be seen that there were few cracks and pores on the surface of the coated paper mulching film, and some large cracks could not be completely filled by composite coating, but fibers also adhered with the composite coating. In addition to the strength of a single fiber of the original paper mulching film and the
bonding force between the fibers, there is a more important factor in that the coating brings a stronger bonding force between the fibers. By observing the illustration in Figure 11i, it can be seen that the original gap between the fibers was filled and adhered by the coating. When the coated paper mulch film was stretched, the coating itself has a certain strength besides the tensile strength of the original paper mulch film, and the coating enhanced the binding force between the fibers, thus making the composite-coated paper mulch film have stronger mechanical properties.

3.5. Analysis of the Tearing Performance of the Paper Mulching Film

By observing the tearing force–displacement graph in Figure 12, it can be seen that the maximum tearing force of the coated paper mulching film and the original paper mulching film was 4.7 N and 3.7 N, respectively, and the tearing strength of the coated paper mulching film and the original paper mulching film was 19.21 MPa and 19.11 MPa, respectively. According to the data observation and analysis, the tearing strength of the coated paper film was almost the same as that of the original paper film, which shows that the coating had no obvious effect on the tearing strength of the paper film, but it improved the maximum tearing strength of the paper film to some extent.

![Tear graph](image_url)

**Figure 12.** Tear graph.

Figure 13 shows the tearing process and tearing fracture fibers, respectively. By observing the illustration in Figure 13a, it can be seen that there were many burrs at the fracture, and the fracture was neat, which shows that the paper mulch film was stressed uniformly when it was torn. At the starting point, the right-angle opening of the tearing specimen was the maximum tearing force, which corresponds to the highest point of the curve in the tearing graph in Figure 12. When the maximum tearing force was reached, a slight inclination angle appeared at the right-angle opening, indicating that the included angle of the notch was less than 90 during the tearing process, which was a stable tearing period [28], so the tearing curve in Figure 12 shows a trend of rising first and then falling. It can be seen from Figure 13b that the number of fine burrs in the tearing fracture increased, and the coarse single fiber fracture had a certain inclination angle, as shown in Figure 13d, which shows that the fiber did not break flat during the tearing process of the paper mulching film sample, but corresponded to the tearing gap, which shows that when a single fiber was torn, the force of the cylindrical or flat fiber was not along the same horizontal plane, but exerted from one stress point to the periphery. The fiber not only broke along the tear opening but also relied on the force all around, so the surface of a single fiber was peeled off, which indicated that the force was uniform in the tearing process and the torn sample broke smoothly.
3.6. Analysis of the Tensile Properties of the Paper Mulching Film at Different Temperatures

Figure 14 shows the graph of the influence of temperature on the tensile properties of the original paper mulch film and the coated paper mulch film. An overall observation of the tensile–displacement curves in the four figures in Figure 14 shows that with the gradual decrease in temperature, the tensile curves of the original paper mulch film and the coated paper mulch film showed a slight downward trend. Although the temperature decreased, this did not affect the tensile properties of the coated paper mulch film, which were superior to those of the original paper mulch film. By analyzing the tensile properties of the original paper mulch film and coated paper mulch film, it was found that the bonding between the fibers of the original paper mulch film was not good, and there were large pores between the fibers. When the temperature rose, the fibers underwent thermal expansion, and then the fibers became soft, making more fibers bond together and filling some pores between the fibers. The area with fewer fibers, that is, the area with large pores, could only be partially filled, which easily caused stress transfer and interface debonding when the paper was subjected to external tension, thus affecting the mechanical properties of the paper. At high temperatures, the surface of the coated paper mulch film was smoother, the uniformity was better, and there were fewer pores in the bonding area between the fibers, which was due to the adhesion between the ZnO/SiO$_2$ composite coating and the fibers, which improved the interfacial adhesion between the fibers, reduced the separation between the fibers and improved the mechanical properties of the paper mulch film. By observing and analyzing the tensile curve in Figure 14, the tensile properties of the coated paper mulch film were less improved than those of the original paper mulch film, because the paper mulch film was formed by bonding fibers to a certain area, and the strength of the fibers themselves also affects the strength of the ZnO/SiO$_2$ composite coating material, and the fibers play a skeleton role in the paper mulch film, thus improving the mechanical properties of the ZnO/SiO$_2$ composite coating material by virtue of its excellent strength characteristics.

According to the overall observation and analysis of the tensile curve in Figure 14, with the decrease in temperature, the tensile properties of the coated paper mulch film and the original paper mulch film decreased slightly, which showed that the low temperature affects the shrinkage of the paper mulch film during freezing, and the fiber length shortened and the environmental humidity increased [29], which made the bonding between fibers not as tight, changed the strength of the fibers themselves, and decreased the overall mechanical properties of the fibers. In the process of freezing shrinkage of the paper mulch film, the surface density of the ZnO/SiO$_2$ composite coating increased, and the air permeability of the paper mulch film decreased obviously, which made the bonding between the ZnO/SiO$_2$ composite coating material and the fibers closer and improved the influence of low temperature on the mechanical properties of the paper mulch film.
were intertwined by mechanical winding, and there was no strong binding force. In the performance of the original paper mulch film were slightly improved [30]. With the increase in temperature, the fiber expansion increased, the length increased, the pores decreased, and this binding force had little effect on resisting external forces. Although the ZnO/SiO$_2$ composite coating material modified the fiber surface, which improved the mechanical strength of the paper mulching film, in the tearing process, the phenomenon of “lint and powder removal” appeared, which made the coating have no obvious effect on the improvement in the mechanical properties of the paper mulching film.

The tearing curve in Figure 15 is observed and analyzed as a whole. With an increase in temperature, the tearing performance of the coated paper mulch film and the tensile performance of the original paper mulch film were slightly improved [30]. With the increase in temperature, the fiber expansion increased, the length increased, the pores decreased, the bonding between the fibers was tight, and the mechanical properties were improved.

Figure 14. (a) High temperature tensile graph, (b) Normal temperature tensile graph, (c) Low temperature tensile graph, (d) Ultra-low temperature tensile graph.

3.7. Tear Performance Analysis of the Paper Mulch Film at Different Temperatures

Figure 15 shows the high temperature tear graph, the normal temperature tear graph, the low temperature tear graph, and the ultra-low temperature tear graph, respectively. When the overall observation temperature decreased, the tearing properties of the coated paper mulch film and the original paper mulch film decreased, mainly because the fibers were intertwined by mechanical winding, and there was no strong binding force. In addition, the temperature was low, the fibers were shortened, and this binding force decreased, therefore, in the tearing process, this binding force had little effect on resisting external forces. Although the ZnO/SiO$_2$ composite coating material modified the fiber surface, which improved the mechanical strength of the paper mulching film, in the tearing process, the phenomenon of “lint and powder removal” appeared, which made the coating have no obvious effect on the improvement in the mechanical properties of the paper mulching film.
1. The ZnO/SiO$_2$ composite coating changed the surface morphology of the paper mulch film, and the superhydrophobic surface of the paper mulch film was obtained by constructing a micro-rough structure on the smooth fiber surface of the paper mulch film. The contact angle of the paper mulching film was increased from 131.53 ± 1.50° to 161.46 ± 1.50°. After mechanical torsion, the contact angle of the paper mulching film still reached 153.15 ± 1.50°, which meant it had better hydrophobic durability.

2. At normal temperatures, the coating improved the mechanical properties of the paper mulch film. The ZnO/SiO$_2$ composite coating played the role of covering, filling, and surface modification in the paper mulching film, effectively reducing the pores and cracks on the surface of the paper mulching film.

3. At high temperatures, the tensile properties of the paper mulching film were improved, because higher temperatures make the bonding between the fibers tighter and the binding force stronger. Tearing performance was not obviously improved. Although the bonding between the fibers was tight with an increase in temperature, the expansion of the fibers increased, cracks appeared on the surface, and the strength of the fibers decreased.

4. At low temperatures, the tensile properties of the paper mulching film decreased, mainly due to the increase in environmental humidity, the freezing shrinkage of the fibers affected the adhesion between them and caused strength changes. Low temperatures affected the mechanical winding and interweaving between the fibers, reduced the tearing performance, and presented the phenomenon of “lint and powder removal”.

Figure 15. (a) High temperature tear graph, (b) Normal temperature tear graph, (c) Low temperature tear graph, (d) Ultra-low temperature tear graph.

4. Conclusions
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