Moisture absorption properties of biomimetic laminated boards made from cross-linking starch/maize stalk fiber

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Abstract: In the research, three kinds composite materials of biomimetic laminated boards made from cross-linking starch/maize stalk fiber—the single layer jute fiber reinforced maize stalk fiber boards, the dual layer jute fiber reinforced maize stalk fiber boards, the jute fiber hybrid reinforced maize stalk fiber boards were obtained according to the formulation of cross-linking maize starch adhesive and the preparation process of composite materials. The hygroscopicity variation of the biomimetic laminated boards made from cross-linking starch/maize stalk fiber was investigated under different relative humidity conditions. The moisture absorption rate and the variation velocity were used as important evaluation indexes to evaluate the moisture absorption properties of the straw fiber composites. The mathematical models of the moisture absorption rate and the variation velocity were established. The hygroscopicity variation curves of three kinds of composite materials were measured under the five different relative humidity conditions. The results showed that the three kinds composites had low moisture absorption rate compared with other stalk fiber composites which were good at water resistance and the waterproof property of the three kinds stalk fibers were excellent under the experimental conditions. The research provides a useful reference to improve the water resistance of fiber composites and a new idea on the development and application of the biodegradable composites, especially the straw fiber reinforced composites.

Keywords: straw, stalk fiber, starch, composite, moisture absorption property, laminated boards
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1 Introduction

With the increasing applications and growing productions of plastics, the plastic products have become an indispensable part of people's life. However, environmental pollution caused by plastic wastes has become a serious problem. Therefore, the development of biodegradable materials has become a research focus. The composite materials prepared with biological fibers have unique advantages, such as lighter weight, lower price, easier processing, renewable and biodegradable. The composite materials prepared with biological fibers have been developed for several decades in the fields of industry and agriculture aiming at reducing pollution of plastic wastes. The plant fiber as natural polymers are abundant and have many special properties, such as high aspect ratio, high specific strength, high specific surface area, low density and bio-degradation. Stalk fiber is one of the important plant fibers. By comparing with other fiber reinforced composite materials, the stalk fiber reinforced composite materials have excellent

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characteristics of lighter weight, lower price, better machinability and biodegradation. Biomimetic laminated boards made from cross-linking starch/maize stalk fibers can be used as potential biodegradable materials in place of plastics due to the advantages of the stalk fibers reinforced composites included adequate specific properties, low material cost, simple production process, non-polluting and acceptable biodegrade ability[1].

The waterproof property of biomimetic laminated boards made from cross-linking starch/maize stalk fibers have a great influence on the properties of composite materials, especially the mechanical properties and the biodegradability cycle. The moisture absorption process of the composites depends on the combined effect in the several processes, which are the absorption and diffusion of water molecules in the fiber and the matrix, the capillary action of water molecules along the fiber-matrix interface and the aggregation action of water in the pores, micro-cracks and interfacial debonding.

In the research, the self-made biomimetic laminated boards made from cross-linking starch/maize stalk fibers were used as experimental materials. The five different relative humidity atmospheres prepared by using saturated salt solution humidity methods was used to determine the moisture absorption rate of biomimetic laminated boards made from cross-linking starch/maize stalk fibers. The moisture absorption rate and the variation velocity were used as important evaluation indexes to evaluate the moisture absorption properties of straw fiber composites. The evaluation indexes provided a useful reference for the water-repellent property of biomimetic laminated boards made from cross-linking starch/maize stalk fibers[2-5].

2 Materials and method

2.1 Experimental materials and equipment

In the experiment, the prepared composite materials were used as biomimetic laminated boards made from cross-linking starch/maize stalk fibers. The saturated salt solution was respectively made from lithium chloride, magnesium chloride, sodium bromide, sodium chloride and potassium nitrate (Beijing Chemical Works). The DT-100 electronic balance (G&G Measurement Plant) and the FA2004 electronic balance (Shanghai Balance Instrument Factory) were used to weigh the composites and analytical reagent. Furthermore, there were also other instruments included dryers, Erlenmeyer flask, graduated cylinder, pipettes, hygrometer, thermometer and vernier caliper.

The best combination of factors of maize starch adhesives based on starch of 10 g, i.e. 125 g of water content, 0.10 g of gelatinization agent (NaOH) and 0.03 g of cross-linking agent ($Na_2B_4O_7 \cdot 10H_2O$) was used as adhesive for the preparation of the biomimetic boards. The cross-linking starch/maize stalk fiber composites were prepared by uniformly mixed the cross-linking maize starch adhesive and 100 g straw fiber composites[6-9]. The biomimetic boards were prepared at 7 MPa of hot-pressing pressure and 150°C of hot-pressing temperature based on the preparation parameters of the biomimetic laminated boards shown as Figure 1.

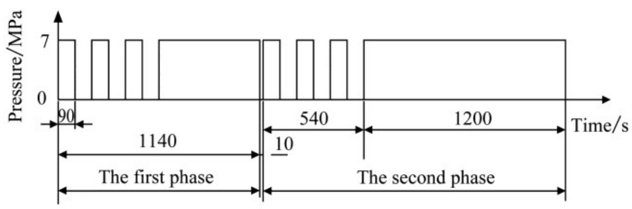


Figure 1 Preparation parameters of the biomimetic laminated boards

Three forms composite materials of the biomimetic laminated boards made from cross-linking starch/maize stalk fiber--the single layer jute fiber reinforced maize stalk fiber boards, the dual layer jute fiber reinforced maize stalk fiber boards, the jute fiber hybrid reinforced maize stalk fiber boards were obtained according to the formulation of the cross-linking maize starch adhesive and the preparation process of composite materials.

2.2 The saturated salt solution humidity method

RH (relative humidity) is a ratio of absolute humidity and saturated humidity under the same temperature and pressure. The different relative humidity atmosphere was prepared by using the saturated salt solution humidity methods in the experiment. A group of sealed glass containers were charged with several saturated solution which are selected. After the air above the containers stirred, the containers were put in the water bath. After a period of time, when vapor space, liquid temperature and bath temperature which above the saturated saline solution completely balanced, the vapor space of the solution had strict constant relative humidity. In the experiment, the five different relative humidity atmospheres was prepared by placing five kinds saturated salt solution, which were Lithium Chloride, Magnesium Chloride, Sodium Bromide, Sodium Chloride and Potassium Nitrate, respectively into the five desiccators. Then, the five different relative humidity atmospheres was used to determine the moisture absorption rate of the composite materials[7-12]. The relative humidity of the corresponding saturated salt solution used in the experiment was shown in Table 1.

Table 1 Saturated saline solution and its corresponding RH (20°C)

Saturated saline solution	Lithium Chloride	Magnesium Chloride	Sodium Bromide	Sodium Chloride	Potassium Nitrate
RH/%	11	33	59	75	95

2.3 Evaluation methods of the moisture absorption properties

The moisture absorption rate and the variation velocity were used as important evaluation indexes to evaluate the moisture absorption properties of the straw fiber composites. And w was defined as the moisture absorption rate (%), i.e. the component of moisture that unit mass of straw fiber composites absorb. The effectiveness of the moisture absorption rate can be found from the below equation:

$$w = \frac{w_t - w_0}{w_0} \times 100\%$$

where, w_t was the mass of the straw fiber composites when time was t; w_0 was the original mass of the dried straw fiber composites.

The relationship between moisture absorption rate and time was concluded according to the curve shape of the moisture absorption rate changed with time. The power function with constant term was got by fitting the moisture absorption rate data of the composites with nonlinear regression. The relationship between moisture absorption rate and time can be found from the below equation:

$$w = a + bt^c$$

where, a, b, c were constants.

The method to obtain the variation velocity of moisture absorption rate was to take moisture absorption rate models a derivative of time. The relationship between the variation velocity and the time can be found from the below equation:

$$v = \mathrm{d}w/\mathrm{d}t = bct^{c-1}$$

3 Results

The moisture absorption rate curves of the single layer jute fiber reinforced maize stalk fiber boards were measured under the condition of five different relative humidity values, as shown in Figure 2.

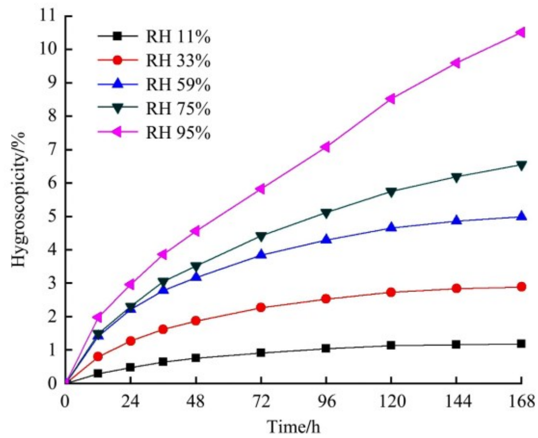


Figure 2 Hygroscopicity of the single layer jute fiber reinforced maize stalk fiber boards under different relative humidity conditions

The mathematical models of the moisture absorption rate and the variation velocity were concluded by fitting the moisture absorption rate data of the single layer jute fiber reinforced maize stalk fiber boards with nonlinear regression[13-19]. And the mathematical model parameters of the moisture absorption rate were shown in Table 2.

Table 2 Hygroscopicity parameters of the single layer jute fiber reinforced maize stalk fiber boards

RH/%	a	b	c	Correlation coefficient r^2
11	-0.026	0.135	0.441	0.981
33	-0.048	0.367	0.417	0.986
59	-0.070	0.629	0.417	0.980
75	-0.068	0.478	0.518	0.990
95	0.071	0.339	0.669	0.999

The moisture absorption rate curves of the dual layer jute fiber reinforced maize stalk fiber boards were measured under the condition of five different relative humidity environments, as shown in Figure 3. The mathematical models of moisture absorption rate and the variation velocity were concluded by fitting the moisture absorption rate data of the dual layer jute fiber reinforced maize stalk fiber boards with nonlinear regression. And the mathematical model parameters of moisture absorption rate were shown in Table 3.

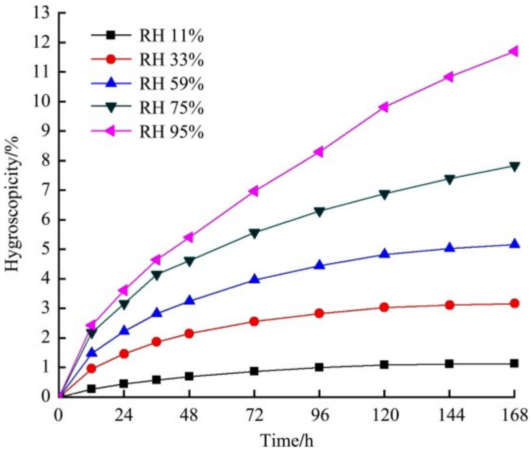


Figure 3 Hygroscopicity of the dual layer jute fiber reinforced maize stalk fiber boards under different relative humidity conditions

Table 3 Hygroscopicity parameters of the dual layer jute fiber reinforced maize stalk fiber boards

RH/%	*a*	*b*	*c*	Correlation coefficient r^2
11	-0.025	0.116	0.463	0.982
33	-0.050	0.465	0.390	0.984
59	-0.069	0.628	0.424	0.991
75	-0.064	0.819	0.446	0.997
95	0.019	0.513	0.612	0.999

The moisture absorption rate of the jute fiber hybrid reinforced maize stalk fiber boards were measured under the condition of five different relative humidity environments. Because the addition of jute fiber treated with NaOH was different, three different kinds jute fiber hybrid reinforced maize stalk fiber boards were prepared, which were the first group of jute fiber hybrid reinforced maize stalk fiber boards (3 g jute fiber—100 g straw fiber), the second group of jute fiber hybrid reinforced maize stalk fiber boards (5 g jute fiber—100 g straw fiber) and the third group of jute fiber hybrid reinforced maize stalk fiber boards (7 g jute fiber—100 g straw fiber)[1,2]. The moisture absorption rate curves of three different kinds jute fiber hybrid reinforced maize stalk fiber boards were shown in Figures 4-6.

The mathematical models of moisture absorption rate and the variation velocity were concluded by fitting the moisture absorption rate data of the jute fiber hybrid reinforced maize stalk fiber boards with nonlinear regression. And the mathematical model parameters of moisture absorption rate were shown in Tables 4-6.

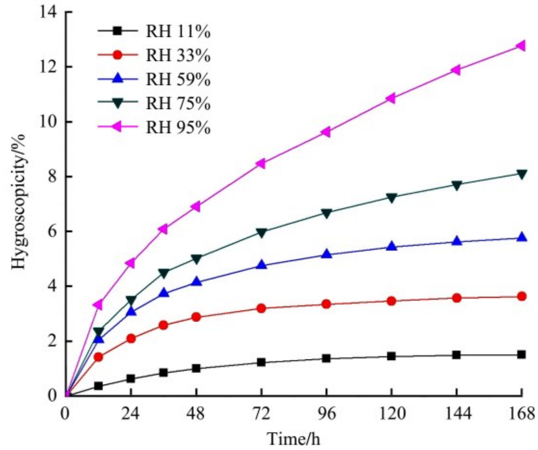


Figure 4 Hygroscopicity of the first group of jute fiber hybrid reinforced maize stalk fiber boards under different relative humidity conditions

Table 4 Hygroscopicity parameters of the first group of jute fiber hybrid reinforced maize stalk fiber boards

RH/%	*a*	*b*	*c*	Correlation coefficient r^2
11	-0.039	0.189	0.425	0.972
33	-0.041	0.884	0.288	0.975
59	-0.063	1.105	0.333	0.987
75	-0.077	0.984	0.418	0.995
95	-0.029	1.021	0.494	1.000

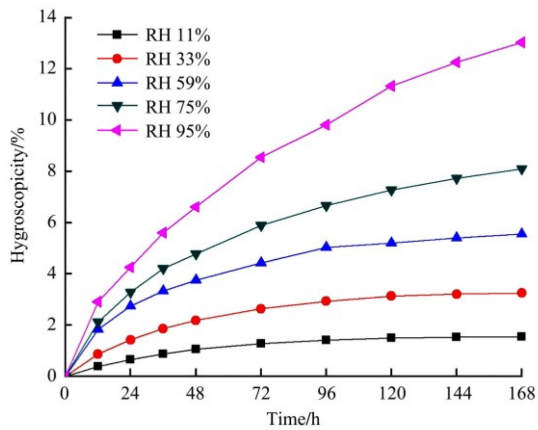


Figure 5 The hygroscopicity of the second group of jute fiber hybrid reinforced maize stalk fiber boards under different relative humidity conditions

Table 5 Hygroscopicity parameters of the second group of jute fiber hybrid reinforced maize stalk fiber boards

RH/%	*a*	*b*	*c*	Correlation coefficient r^2
11	-0.040	0.201	0.419	0.971
33	-0.069	0.432	0.412	0.978
59	-0.066	0.888	0.369	0.988
75	-0.097	0.826	0.454	0.995
95	-0.090	0.782	0.555	0.998

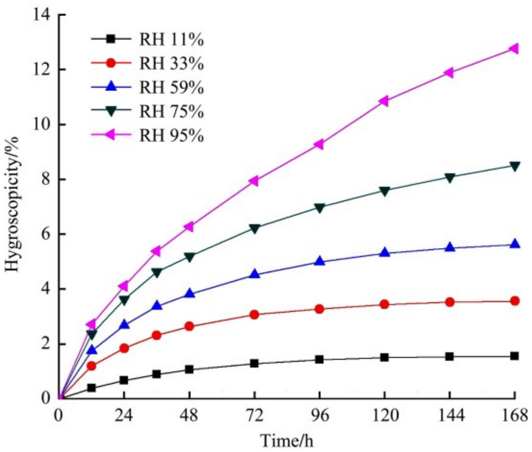


Figure 6 Hygroscopicity of the third group of jute fiber hybrid reinforced maize stalk fiber boards under different relative humidity conditions

Table 6 Hygroscopicity parameters of the third group of jute fiber hybrid reinforced maize stalk fiber boards

RH/%	*a*	*b*	*c*	Correlation coefficient r^2
11	-0.039	0.206	0.414	0.971
33	-0.055	0.676	0.340	0.977
59	-0.079	0.861	0.379	0.986
75	-0.090	0.978	0.429	0.995
95	-0.040	0.681	0.575	0.999

For the five kinds of biomimetic laminated boards made from cross-linking starch/maize stalk fiber, except for the mass and arrangement of jute fiber, the mass of straw fiber, the formulation and the mass of the cross-linking maize starch adhesive and the preparation of the straw fiber composites were all the same. Thus, the moisture absorption rate of cross-linking starch/maize stalk fiber composites is relatively close.

4 Discussion

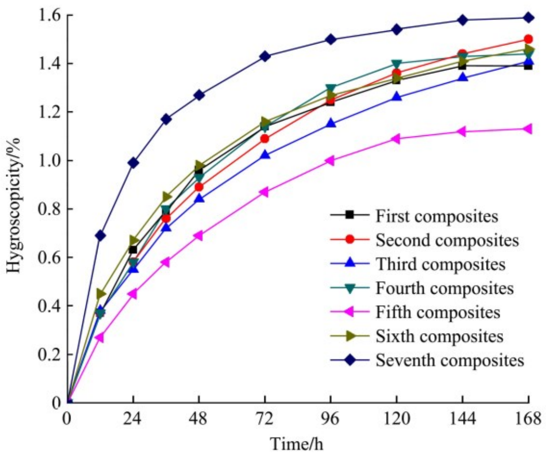
The research is aiming at improving the water resistance of straw fiber composites. In order to distinguish the moisture absorption rate of several kinds biomimetic laminated boards made from cross-linking starch/maize stalk fiber, the moisture absorption rate of composites prepared in the experiment was analyzed.

The dual layer jute fiber reinforced maize stalk fiber boards was a better straw fiber composites for the water resistance at the relative humidity of 11%. And at other relative humidity of 33%, 59%, 75% and 95%, the single layer jute fiber reinforced maize stalk fiber board was a better composite for the water resistance. At different relative humidity, the better straw fiber composites for the water resistance were shown in Table 7.

Table 7 The better composites of the biomimetic boards for the water resistance

RH/%	Biomimetic laminated boards made from cross-linking starch/maize stalk fiber
11	The dual layer jute fiber reinforced maize stalk fiber boards
33	The single layer jute fiber reinforced maize stalk fiber boards
59	The single layer jute fiber reinforced maize stalk fiber boards
75	The single layer jute fiber reinforced maize stalk fiber boards
95	The single layer jute fiber reinforced maize stalk fiber boards

In the research, the moisture absorption rate of the biomimetic laminated boards made from cross-linking starch/maize stalk fiber was compared with several other straw fiber composite materials which are good at water resistance (the yellow dextrin/straw fiber composites, the starch/maize stalk fiber composites, the cross-linking starch/maize stalk fiber composites, the yellow dextrin/ straw fiber composites optimized with composites flexural properties, the cross-linking starch/maize stalk fiber composites optimized with composites flexural properties, biomimetic laminated boards made from the yellow dextrin/straw fiber composites)[1,2]. The moisture absorption rate curves of straw fiber composites were measured at different relative humidity, as shown in Figures 7-11. Except for Figure 9, the moisture absorption rate of biomimetic laminated boards made from the cross-linking starch/maize stalk fiber composites can be seen from Figures 7-11 was smallest, i.e. the waterproof property was the best among the experimental composites. The research proved that the water resistance of straw fiber composites prepared by crosslinking starch adhesive has been significantly improved. The cross-linking agent can form a ligand with the hydroxyl group of the starch adhesive to generate the multinuclear complex which is network structure, as a result, the effect increase the viscosity of starch adhesive and fix it well on the straw fibers with hydroxyl groups. Consequently, the density of straw fiber composite material has been optimized and the water resistance improved.



Note: First composites—the yellow dextrin/ straw fiber composites; Second composites—the starch/maize stalk fiber composites; Third composites—the cross-linking starch/maize stalk fiber composites; Fourth composites—biomimetic laminated boards made from the yellow dextrin/straw fiber composites; Fifth composites—biomimetic laminated boards made from cross-linking starch/maize stalk fiber composites; Sixth composites—the yellow dextrin/straw fiber composites optimized with composites flexural properties; Seventh composites—the cross-linking starch/maize stalk fiber composites optimized with composites flexural properties. Same as below.

Figure 7 Hygroscopicity of seven kinds straw fiber composites at RH of 11%

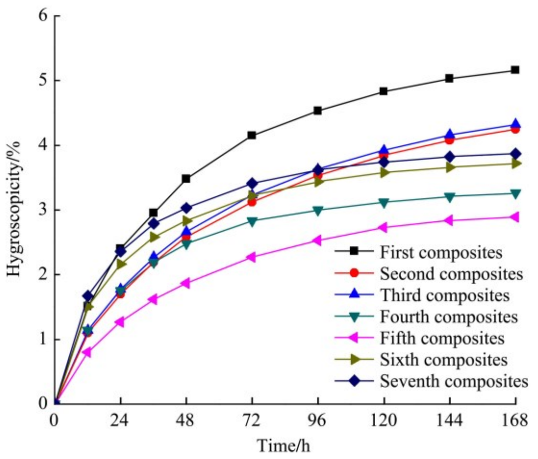


Figure 8 Hygroscopicity of seven kinds straw fiber composites at RH of 33%

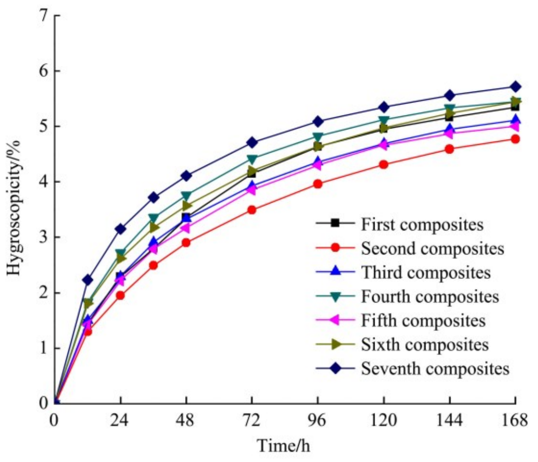


Figure 9 Hygroscopicity of seven kinds straw fiber composites at RH of 59%

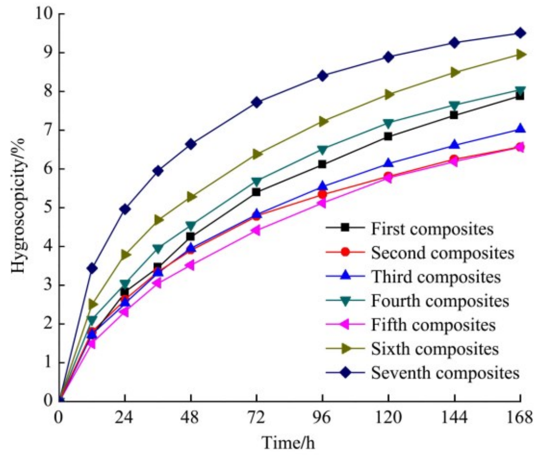


Figure 10 Hygroscopicity of seven kinds straw fiber composites at RH of 75%

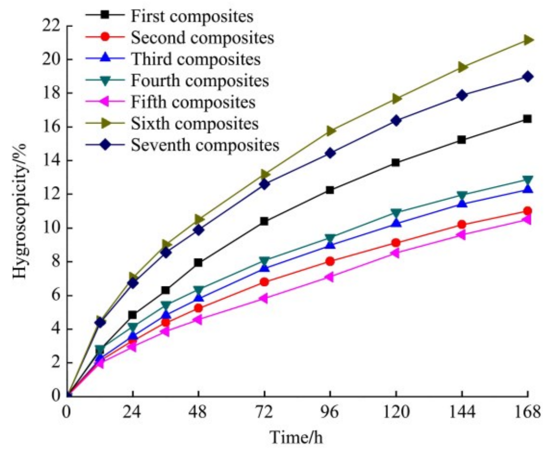


Figure 11 Hygroscopicity of seven kinds straw fiber composites at RH of 95%

5 Conclusions

In the research, the moisture absorption rate of three forms composites of biomimetic laminated boards made from cross-linking starch/maize stalk fiber were measured at different relative humidity, then, the models of moisture absorption rate and the variation velocity were concluded.

The moisture absorption rate of biomimetic laminated boards made from cross-linking starch/maize stalk fiber were compared with several other straw fiber composites which are good at water resistance (the yellow dextrin/ straw fiber composites, the starch/maize stalk fiber composites, the cross-linking starch/maize stalk fiber composites, the yellow dextrin/straw fiber composites optimized with composites flexural properties, the cross-linking starch/maize stalk fiber composites optimized with composites flexural properties, biomimetic laminated boards made from the yellow dextrin/ straw fiber composites) at different relative humidity atmospheres. Then, the models of moisture absorption rate and the variation velocity were concluded, the moisture absorption rate curves of each straw fiber composites were analyzed at the same relative humidity. Under the experimental conditions established, moisture absorption rate of the several kinds straw fiber composites were analyzed at different relative humidity and moisture absorption rate curves of seven straw fiber composites were drawn at different relative humidity atmospheres. The research showed that the water resistance of straw fiber composites prepared by crosslinking starch adhesive has been significantly improved. It prove that among these straw fiber composites mentioned in the research, the moisture absorption rate of biomimetic laminated boards made from the cross-linking starch/maize stalk fiber composites was the smallest, that is, its water-repellent property was the best.

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