

# EFFECTS OF DIFFERENT PLASTIC FILMS MULCHING ON SOIL TEMPERATURE AND MOISTURE AND FILM MECHANICAL PROPERTY

## 不同地膜覆盖对土壤温湿度及地膜力学特性的影响

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### ABSTRACT

The purpose of this research was to study heat and moisture retention and breaking force properties of different plastic mulches. The field experiments with different plastic mulches were carried. The results showed that, the fracture strength and the right-angle tear strength of reinforced mulch are superior to those of weather-resistant mulch and ordinary mulch. The soil moisture, humidity and daily mean temperature under plastic mulches were affected by the laying time at a 1% probability level. It was also found that the variety had no significant effect on daily mean temperature under plastic mulches. A strong correlation was found between breaking force and the laying time of plastic film. A multiple linear regression model was developed to determine the relationship between the heat and moisture retention properties and breaking force. The  $R^2$  values of three plastic mulch varieties regression model were 0.904, 0.913 and 0.931. The breaking force of reinforced mulch and weather-resistant mulch indicates that plastic mulch recovery should be conducted after autumn, before it is too weakened by exposure.

### 摘要

本研究旨在探讨不同塑料地膜的保热保湿性及破断力特性。进行了不同地膜覆盖的田间试验及破裂力试验。结果表明，加强型地膜的断裂强度和直角撕裂强度均优于耐候地膜和普通地膜。地膜覆盖对土壤水分、湿度和日平均温度受铺膜时间的影响十分显著 ( $P < 0.01$ )。不同品种对地膜覆盖下的日平均气温无显著影响。破断力与覆膜时间有较强相关性。建立了多元线性回归模型，确定了地膜下土壤温湿度与破断力的关系，三个地膜覆盖回归模型的  $R^2$  值分别为 0.904、0.913 和 0.931。以免地膜强度过低，地膜回收应在棉花收获后立即进行。

### INTRODUCTION

Plastic film mulching planting technology was introduced into China from Japan in the 1970s. Since then, it has become an important agricultural practice for increasing grain yields and crop productivity by conserving soil humidity, increasing soil temperature, and increasing the yields of crops by more than 20%, driving its widespread use (Hou S, et al., 2002; Hu C, et al., 2020; Liu E, et al, 2014). Plastic film mulching has been especially important in Xinjiang, considering its geographical location characterized by a dry climate and low spring temperatures. Film mulching has developed rapidly and has been widely used in Xinjiang since its introduction in 1983 (Yan C, et al, 2016). The area of mulched planting in Xinjiang exceeded 3 million ha by 2018, accounting for nearly 20% of China's total agricultural areas covered in plastic mulching (Gao W & Han R, 2019). However, despite the large amount of plastic mulches put into use, only a small fraction of these polyethylene films is currently recycled because of the expense and time required for its recycling (Gao, H, et al, 2019). Most of the mulch film residues remain in the soil owing to the lack of timely recovery of plastic film each year (Xue Y, et al., 2017), and the residue thus accumulates year by year. The physical structure of soil is also changed by film residue (Zhao Y, et al., 2017). The soil porosity and permeability are reduced, while the movement of water and fertilizer in the soil is impeded (Yang N, et al., 2015). It also hinders the movement of agricultural machinery in the soil (He C, et al., 2019).

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In addition, the residues can deteriorate the soil structure, become entangled with crop roots, and inhibit the absorption of water and nutrients. These issues directly affect the root length, root surface area, and vigour of crops (Yan C, *et al.*, 2008; Zhang K, *et al.*, 2020), resulting in reduced crop production and "White pollution", and the sustainable development of agriculture in China has thus been affected seriously (Qi Y, *et al.*, 2018). Heat and moisture retention are the main function of plastic mulch. The research on the performance of heat and moisture retention of film focuses on biodegradation film (Gao H, *et al.*, 2019; Kyrikou & Briassoulis, 2007). The effects of increasing soil moisture and temperature were present well at the early stage, biodegradation film is thus recommended as a viable option to the plastic film, but it should be carefully selected according to local environmental conditions (Zhang Y, *et al.*, 2018). Many studies have been conducted on the characteristics of mulch film. The changes in the tensile properties of mulch film are affected by the environment at different timescales, and studies of its thickness and position have shown that the tensile strength of plastic film is greatly affected by both natural conditions and covering time (Zhang J, *et al.*, 2015). Especially in the two months after mulching, the tensile strength decreases significantly, with the tensile strength of the mulch film near to cotton plants being higher than that of the mulch film far from cotton plants, and that of thick film being higher than that of thin film. Though there is much research related to the heat and moisture retention properties of biodegradation film in literature, there is limited information about heat and moisture retention properties of plastic film.

It has been observed that the reinforced mulch, weather-resistant mulch and ordinary mulch are used widely in Xinjiang, which were selected for the present study. The tensile and right-angle tear properties of new plastic films, as well as the relationship between mulching time, daily mean temperature and humidity under the film with breaking force were examined. The relationship between breaking force and these parameters of plastic films is a useful reference for the use and recovery of plastic film in Xinjiang and similar areas.

## MATERIALS AND METHODS

The field experiment was conducted in plot 10 of Alar Farm (40.61°N 81.28°E, 912.3 m above sea level) in 2019. Three kinds of plastic mulch, those that are presently used widely in Xinjiang, were selected for the experiment, namely reinforced mulch (RM), weather-resistant mulch (WM), and ordinary mulch (OM). The dimensions of the plastic mulch are 2050 mm × 0.01 mm (width × thickness), and all plastic mulches used were produced in 2018. Plastic mulch was laid down as shown in Figure 1, and the area of the testing field was 40 m<sup>2</sup> (20 m × 2 m). Local machine-picked cotton was planted in the experimental area, and the cultivation utilized three drip irrigation belts and six rows of cotton plants under plastic mulch. The distance between belts and rows were 660 mm and 100 mm, respectively, with a column spacing of 12.5 cm. The water and fertilizer management followed common local field management practices, with a top dressing applied.

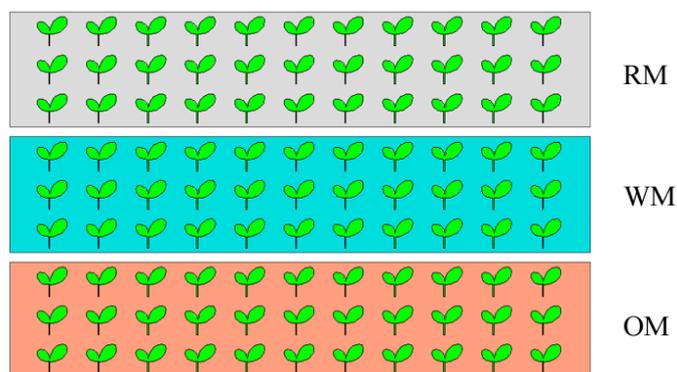


Fig. 1 - Diagram of plastic mulching experiment

To study the mechanical properties of plastic mulch, the three kinds of new plastic films were cut into 500 mm × 1000 mm samples using scissors. Sample surfaces were checked to be free of visible defects, including cracks, breakage, or other defects. The mechanical properties of plastic mulch including tensile and right-angle tear strength. The tensile strength test is common test methods for mechanical properties of materials. Then the right-angle tear strength test is a method for assessing tear resistance of plastic films. The specimen is ultimately torn at a right angle by stretching it. Therefore, the tear strength of the sample is

also an important index of the physical properties of the plastic film. The tear strength of different mulch films is obtained through the right-angle tear test, which provides some reference for the mechanized recovery of plastic film.

Based on the plastic-determination of tensile properties standards (GB/T 1040-2006), a special cutting tool was used to punch the sample into a type II strip sample, with a width and length of 10 mm and 150 mm, respectively (Committee, 2019). Test samples were placed on a 10 kN universal testing machine (model WWD-10J) for testing. During the test, the mulch sample was clamped at both ends with a special fixture, to ensure that the long axis of the specimen aligns with the centreline of the fixture to prevent the mulch sample from sliding relative to the fixture. Accordingly, the clamping force was checked to ensure it was not held in place too firmly or weakly in order to prevent failure of the specimen without it being properly tested. Tests were conducted with a tensile rate of 500 mm/min and initial distance of 50 mm. For materials with yield phenomena, the nominal fracture strain  $\varepsilon_t$  is expressed as shown in Formula (1) (Kassner, Kennedy, & Schrems, 1999):

$$\varepsilon_t = \frac{\Delta L}{L} \times 100\% \quad (1)$$

where,  $\varepsilon_t$  represents the nominal strain of fracture (as a ratio or percentage),  $L$  represents the initial distance between fixtures (in mm), and  $\Delta L$  represents the incremental distance between fixtures (in mm).

The right-angle tear test results provide the maximum load during the process of tearing the material with a right-angle tear load. The right-angle tear strength is expressed in  $\sigma_s$ , as shown in formula (2):

$$\sigma_s = \frac{P}{d} \quad (2)$$

where,  $\sigma_s$  represents the tight angle tear strength, [kN/m],  $P$  represents tear load, [N],  $d$  represents sample thickness, [mm].

Following the test method for right-angle tear properties of plastics standard (QB/T 1130-1991), films were cut in transverse directions into dovetail-shaped samples with a length of 100 mm and width of 20 mm using a special cutter, as shown in Figure 2. Specimens were aligned with the central direction of the two clamps and clamped into the fixture at a certain depth to ensure that the specimen was fully and evenly clamped in the parallel position. The initial distance between the two clamps was 50 mm, one end of which was fixed, while the other end was stretched by the testing machine, such that it moves to stretch the specimen in one direction at a tensile speed of 200 mm/min. Testing was conducted at 22°C and 43% relative humidity.

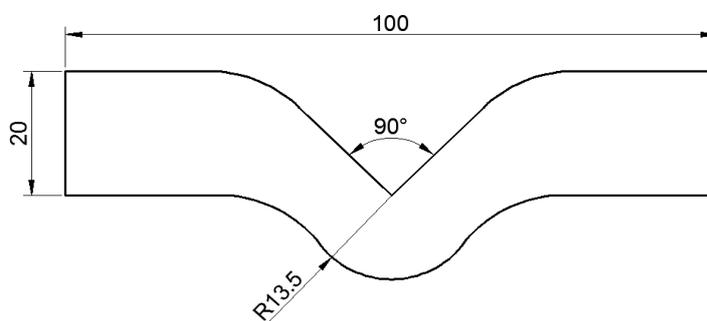


Fig. 2 - Rectangular tear samples

In order to study the heat and moisture retention properties of plastic mulch, during the cotton growing season from May to October, soil moisture, humidity, and daily mean temperature under the plastic mulch as well as ambient temperature were periodically measured. Soil humidity was measured with a MD783 humidity detector, and the measurement range was 2–60% relative humidity. The relative humidity resolution was 0.1%, while the measurement accuracy was  $\pm 1.5\%$ . Humidity in the plastic mulch was measured by a RH87 multifunctional environmental parameter recorder, with a humidity measurement range of 20–80%, a

resolution of 0.1%, and measurement accuracy of  $\pm 3\%$ . Daily mean temperature in the plastic mulch was measured by a buried-soil temperature and humidity sensor.

The breaking force of the plastic film was assessed in the process of it being picked up by the tillage parts of a residual film recovery machine. In order to simulate the mechanized recycling process of plastic mulches, a hook breaking force test was designed; the diagram of the test is shown in Figure 3. The tensile testing instrument was the AFG5 high precision tensile tester, which has a force measuring range of 0–20 N, force resolution of 0.1 N, and measurement accuracy of  $\pm 2\%$  FS. Each sample was stretched at 20 mm/min until the plastic mulch break-off. Each test was repeated 10 times.

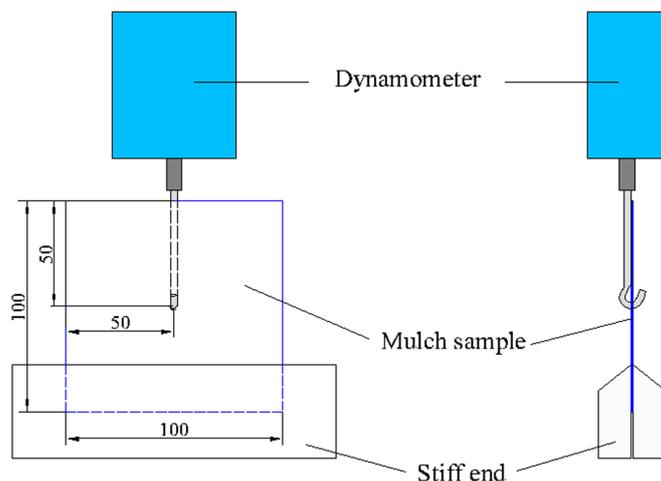


Fig. 3 - Breaking force test for plastic mulch

The data recorded in the field test and breaking force test were statistically analysed using a two-factor randomized complete block design to study the effects of six laying time and three varieties on some heat and moisture retention and breaking force properties explained in this section. Duncan's multiple range test was used to compare the means. Data processing Statistical analysis was done using SPSS 22.0 for Windows. The figures were prepared using the Origin 8.6 software program.

## RESULTS AND DISCUSSION

As shown in Figure 4, the strain-stress curve of plastic mulch exhibits a yield point and a fracture point. It shows that the plastic mulches are all ductile materials. The relationship between stress and strain is approximately linear in the initial loading stage. When the stress reaches the yield point, the stress decreased and then increased until the fracture point. It is generally believed that the yield point corresponds to the destruction of the microstructure. When the stress is lower than this value, the stress does not cause damage to the plastic mulch. The stress and strain continue to increase until the load reaches the maximum, that is, the fracture point shown in the figure. Therefore, the stress at fracture point is viewed as the maximum stress that the plastic mulch can bear.

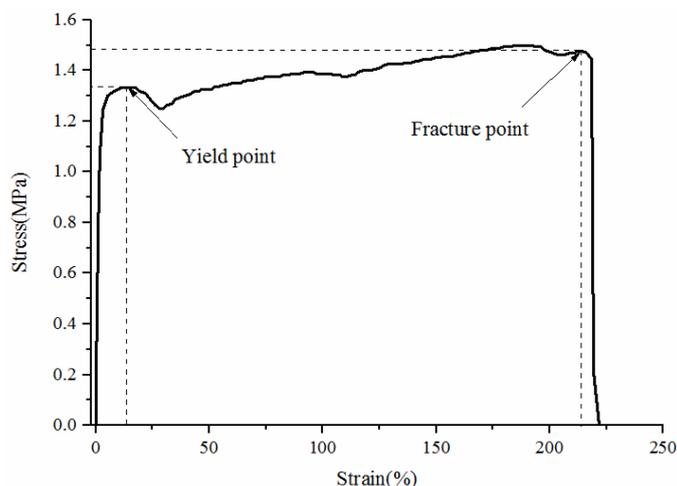
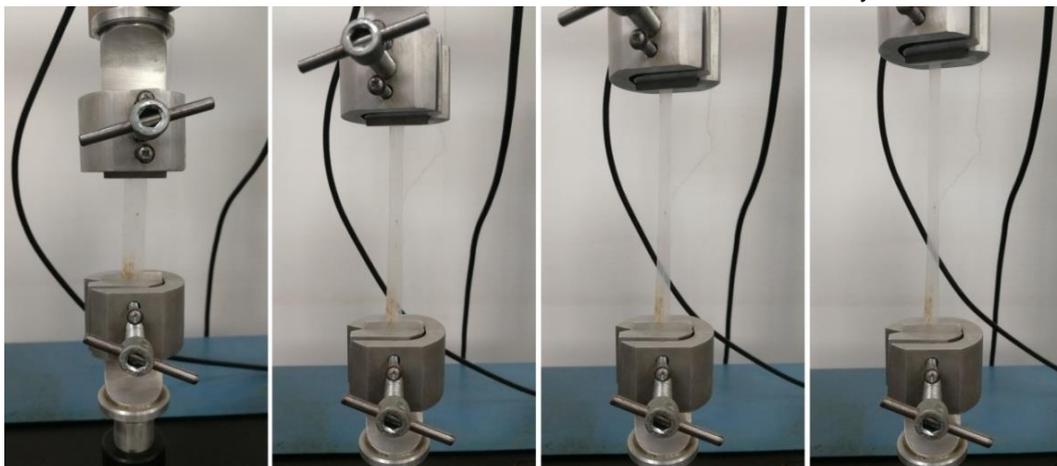


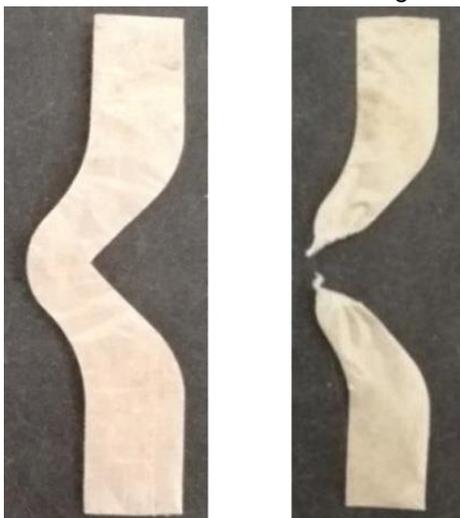
Fig. 4 - A typical strain-stress curve

The tensile testing process is shown in Figure 5, which shows that the film sample is continuously stretched in the images arranged from left to right. The width gradually narrows, and the light transmittance is obviously enhanced. The thickness of the film thins as it stretches until it eventually breaks.



**Fig. 5 - Tensile testing process**

A right-angle tear test sample before and after the test is shown in Figure 6, which demonstrates that the film sample gradually changes from a swallowtail shape to a strip shape in the process of stretching, from a right-angle notch to an eventual tear, and there is a small protuberance at the site of failure in the sample. This shows that the specimen first ruptures from the right-angle notch, then breaks to a certain extent and no longer tears, but instead bears the overall tensile force until fracturing.



**Fig. 6 - A sample (a) before and (b) after right-angle tear testing**

As shown in Figure 7, the right-angle tear curve of plastic mulch exhibits a right-angle tear point. The relationship between force and displacement is approximately parabola distribution in the entire right-angle tear stage. When the force reached the right-angle tear point, the force decreases until the plastic mulch break-off. Therefore, the load at this point is viewed as the maximum right-angle tear force that the plastic mulch can bear.

The fracture stress, fracture strain, right-angle tear strength and strain for the plastic mulch varieties are shown in Table 1. The fracture strain and fracture stress of the reinforced mulch were also the highest, at  $284.60 \pm 10.86\%$  and  $1.66 \pm 0.12$  MPa, respectively. Meanwhile, the right-angle tear strength and strain value of the reinforced mulch were also the highest, at 12.1625 kN/m and 57.51%. The results of Duncan's multiple range tests showed that the difference among the fracture stress, fracture strain, right-angle tear strength and strain were statistically significant for plastic mulch variety. The test results show that the fracture strength and the right-angle tear strength of reinforced mulch are superior to those of weather-resistant mulch and ordinary mulch. The tensile lengths of the three plastic mulches at their breaking points are all satisfactory, with the fracture strain for each of them exceeding 200%.

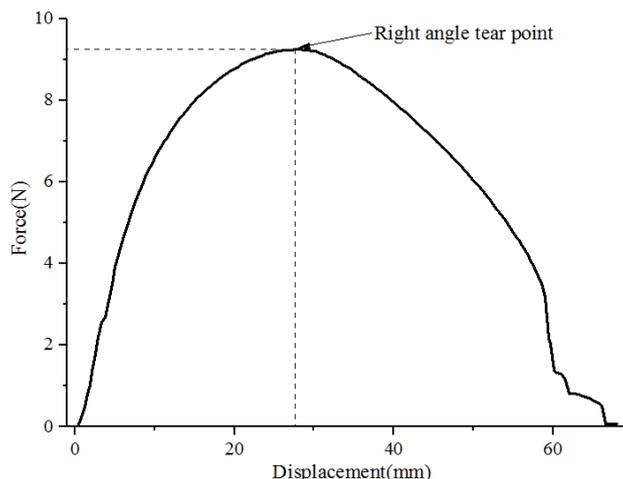


Fig. 7 - A typical right-angle tear curve

Table 1

The mechanical property test results

Variety	Fracture stress (MPa)	Fracture strain (%)	Right-angle tear strength (kN/m)	Right-angle tear strain (%)
RM	1.66±0.12 <sup>a</sup>	284.60±10.86 <sup>a</sup>	12.14±1.54 <sup>a</sup>	57.69±5.34 <sup>a</sup>
WM	1.44±0.15 <sup>ab</sup>	218.27±8.85 <sup>b</sup>	11.55±1.27 <sup>a</sup>	53.66±4.37 <sup>ab</sup>
OM	1.40±0.09 <sup>b</sup>	236.58±10.05 <sup>b</sup>	10.07±1.04 <sup>a</sup>	47.48±4.88 <sup>b</sup>

In each column, means with the same letters are not significantly different at the 0.01 level of significance using Duncan's multiple range test.

The soil moisture, humidity and temperature under each mulch for the plastic mulch varieties are summarized in Table 2.

Table 2

The heat and moisture retention performance test results

Time (D)	Variety	Soil moisture (%)	Humidity (%)	Daily mean temperature (°C)
0	RM	26.30	39.57	18.8
	WM	20.57	37.63	20.8
	OM	14.73	36.70	19.3
17	RM	32.53	68.63	24.5
	WM	22.27	65.37	24.9
	OM	21.70	61.53	23.5
45	RM	30.13	64.43	28.0
	WM	27.60	63.37	29.5
	OM	20.83	62.17	26.1
72	RM	43.43	59.60	23.5
	WM	39.43	60.63	25.2
	OM	38.63	58.37	23.1
91	RM	39.73	60.60	24.2
	WM	34.37	59.80	24.6
	OM	38.80	58.70	23.7
104	RM	42.33	64.50	24.3
	WM	39.40	62.70	23.7
	OM	38.97	62.30	23.2
Mean				
	RM	35.74 <sup>a</sup>	59.56 <sup>a</sup>	24.8 <sup>a</sup>
	WM	30.61 <sup>b</sup>	58.25 <sup>ab</sup>	23.9 <sup>a</sup>
	OM	28.94 <sup>c</sup>	56.63 <sup>b</sup>	23.1 <sup>a</sup>
P-value				
T		0.000 <sup>**</sup>	0.000 <sup>**</sup>	0.000 <sup>**</sup>
V		0.000 <sup>**</sup>	0.000 <sup>**</sup>	0.079 <sup>ns</sup>
T×V		0.000 <sup>**</sup>	0.356 <sup>ns</sup>	0.977 <sup>ns</sup>

\*, \*\*: Significant at the levels of 5% and 1%, respectively.

ns: Not significant.

In each column, means with the same letters are not significantly different at the 0.01 level of significance using Duncan's multiple range test.

The soil moisture and humidity under mulches increased as the time increased for plastic mulch varieties. The reason for this is that the test field began to drain water in late May. This relationship was found statistically significant at a 1% probability level. The differences among the humidity values under plastic mulch for varieties were found to be statistically insignificant. The overall soil moisture values varied between 26.30 % and 43.43 % for reinforced mulch, varied between 20.57 % and 39.43 % for weather-resistant mulch, and varied between 14.73 % and 38.97 % for ordinary mulch, respectively. This difference was also found to be statistically significant at a 1% probability level. According to the variance analysis results, the increase in soil moisture and humidity under plastic mulches with time was significant for varieties.

From Table 2, it can be observed that temperature under plastic mulch increased nonlinearly as the time increased. Considering the varieties together, the daily mean temperature values ranged from 18.8°C to 29.5°C. The effect of time on daily mean temperature was also statistically significant at a 1% probability level. However, it was found that daily mean temperature values for plastic mulch varieties were in the same group according to Duncan's multiple range test results.

There is a large area of plastic film coverage in Xinjiang, and there are many brands and types of mulch on the market. Three kinds of plastic mulch were tested for their heat preservation and moisture retention, and temperature and humidity are related to the location and depth of measurements. Accordingly, this testing was conducted in the middle of each cotton row, the temperature and humidity under the film were measured between the film and the soil, and the soil moisture was measured at a 5-cm soil depth. Reinforced mulch was found to have the best moisture retention effect, though the difference between the weather-resistant mulch and the ordinary mulch in this aspect was not large, and the heat retention effect of weather-resistant mulch was also the best. However, the climatic environment and soil conditions in the northern and southern regions of Xinjiang are quite different (Hu C, et al., 2019). Therefore, even within Xinjiang, the test results are not universal, and suitable mulch should be selected according to the planting characteristics of each particular area.



**Fig. 8 - Breaking force test process**

The breaking force test process of the plastic film is shown in Figure 8. During the stretching process of the hook, the plastic film starts to break from the middle point. The rupture point of plastic film is related to the position of hook action. Breaking force of plastic mulch is summarized in Figure 9, which shows that as mulch covering time increased, the hook breaking force decreased gradually. The breaking force of reinforced mulch was the greatest, followed by that of weather-resistant mulch. As mulch covering time increased, the rate of decrease in mulch breaking force also decreased.

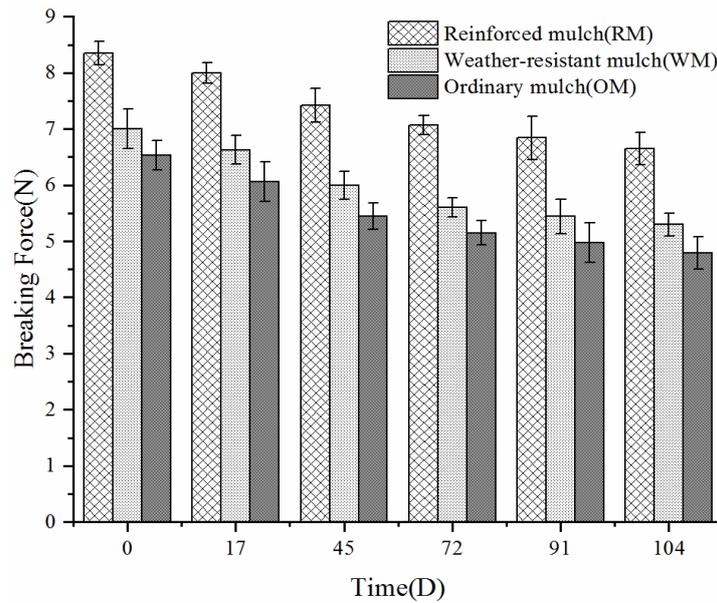


Fig. 9 - Breaking force of plastic mulch

Based on the relationship of mulch covering time, soil moisture, temperature, and humidity with mulch breaking force, the following mathematical model can be established:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \end{bmatrix} \begin{bmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \tag{3}$$

Here,  $y$  represents the estimate of breaking force;  $a$  represents the regression coefficients;  $x_1$  represents the mulch covering time;  $x_2$  represents the soil moisture estimate;  $x_3$  represents the humidity estimate;  $x_4$  represents the daily mean temperature estimate.

Using multivariate linear analysis, coefficient value and significance of each variable was given in Table.3. The breaking force decreased as the time increased for plastic mulch varieties, this relationship was found statistically significant at a 1% probability level. That means that the application time of plastic mulches is the main factor that influence the breaking force.

Table 3

Coefficient value and significance of each variable

Variable	Time	Soil moisture	Humidity	Daily mean temperature
RM	-0.556**	0.712 <sup>ns</sup>	0.057 <sup>ns</sup>	-0.019 <sup>ns</sup>
WM	-0.414**	-2.924 <sup>ns</sup>	0.664 <sup>ns</sup>	-0.040 <sup>ns</sup>
OM	-0.344**	-3.031 <sup>ns</sup>	0.444 <sup>ns</sup>	-0.104*

\*, \*\*: Significant at the levels of 5% and 1%, respectively.  
<sup>ns</sup>: Not significant

By substituting coefficient value into Formula (3), the following multiple linear regression model can be obtained:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} 13.420 & -0.556 & 0.712 & 0.057 & -0.019 \\ 12.176 & -0.414 & -2.924 & 0.664 & -0.040 \\ 12.735 & -0.344 & -3.031 & 0.444 & -0.104 \end{bmatrix} \begin{bmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \tag{4}$$

The fitted values and Mann-Whitney U test results are tabulated in Table.4. As seen in Table.4, the  $R^2$ , Adjusted  $R^2$  and RMSE values all achieve significant effect, indicating that the regression equation obtained has a high degree of fitting. The Mann-Whitney U test values were greater than 0.05, therefore, there is no significant difference between the test data and the prediction data. Obviously, the regression model is suitable to describe the breaking force changes.

Table 4

Fitted values and Mann-Whitney U test results

Variety	$R^2$	Adjusted $R^2$	RMSE	Mann-Whitney U test
RM	0.904	0.875	0.3553	1.000 <sup>ns</sup>
WM	0.913	0.886	0.3296	0.938 <sup>ns</sup>
OM	0.931	0.909	0.3086	1.000 <sup>ns</sup>

*ns: Not significant*

The best time for plastic film recovery is after autumn when the cotton is harvested. At that time, the mulch covering has been in place for approximately 160 days, while the soil moisture, humidity and daily mean temperature under plastic mulches are approximately 32%, 48%, and 26°C, respectively. Based on the mathematical model, the breaking forces of reinforced mulch, weather-resistant mulch, and ordinary mulch are predicted to be 6.2263 N, 5.1061 N, and 4.9239 N, respectively. During the actual removal operation, most of the surface film can be recovered with a force above 5.0 N. The hook breaking force of the reinforced mulch and the weather-resistant mulch can thus meet the mechanical operation requirements. After the cotton harvest, the three types of surface mulch were recovered by a comb-tooth mulching recycling machine. The recovery rates for reinforced mulch were higher than that of weather-resistant mulch and ordinary mulch. The results are consistent with the model predictions.

Comparisons of the coefficients of the mathematical regression model show that mulch laying time has a much greater impact than the other parameters. Accordingly, the performance of mulch film is greatly affected by the mulch covering time period. This result is consistent with previous studies, in the early stage of the mulch covering time period, the performance of the cutting force decreased substantially. The hook breaking force performance of plastic film also decreases with the time of mulch covering. Therefore, plastic film should be recovered as soon as possible after the autumn harvest of each year. Otherwise, longer mulch covering time periods increases the difficulty of recycling.

## CONCLUSIONS

The mechanical properties, heat and moisture retention performance and breaking force for three typical plastic mulches widely used in Xinjiang were measured. A breaking force regression model was established by fitting the field experiment and breaking force data using multiple regression method. The results indicate that the fracture strength and the right-angle tear strength of reinforced mulch are superior to those of weather-resistant mulch and ordinary mulch. The different plastic mulches exhibited significant differences in soil moisture retention and breaking force, and insignificant differences in humidity and daily mean temperature under plastic mulches. The correlation analysis showed that soil moisture and humidity under plastic mulches were significantly correlated with the laying time and plastic mulch varieties, whereas the temperature under plastic mulch and breaking force were significantly correlated with the laying time at a 1% probability level. The significant factor of the breaking force was the laying time. The breaking force was predicted and evaluated based on the laying time, soil moisture, humidity and daily mean temperature under plastic mulches. The mathematical model predicts that the hook breaking force of the reinforced mulch and the weather-resistant mulch can meet the requirements of film recovery after autumn. This study evaluated the heat and moisture retention performance and breaking force of commonly used plastic mulches in Xinjiang and provides reference data to develop suitable conditions for plastic mulches use and recycling.

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