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WATER VAPOR PERMEABILITY OF LEATHERS BY GREY SYSTEM THEORY

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Abstract. In this paper, Grey System Theory (GST) is used to study the water vapor permeability of leathers. Grey relation analysis was employed to analyze the main affecting factors, and the contributions of each factor to the water vapor permeability of leathers were investigated and compared. The relation equations between time and the water vapor permeability of leathers were obtained by computer calculation. The results indicated that Grey System Theory can be used to investigate and calculate the water vapor permeability of leathers, and the technique is effective and convenient.

1. INTRODUCTION

Water vapor permeability is one of the most precious physical properties of leathers, which may greatly affects the breathability and the comfortable feelings of leather goods [1]. There are plenty of capillaries among collagen fibers in leathers as well as lots of hydrophilic groups on the collagen chains. They may endow leathers with good water vapor permeability, compared with other synthetic clothing-materials [2].

The water vapor permeability cup is a popular method to determine the water vapor permeability. Ideal results may usually be obtained for the materials with a good humidity resistance. Marcinkowska et. al used the Water Vapor Permeability Cup Method and Prototype-measuring Instrument (Hy-tester) to study the moisture transporting in leather and leather-like materials for clothing and shoes. It was reported that the standard error, as well as total and partial uncertainties, was successfully discussed by the statistical and mathematical analyses [3,4].

There are many factors that may affect the water vapor permeability of leathers. For example, the thickness, density, water-absorbing ability, and aperture ratio of the samples may contribute to the water vapor permeability of leathers. Besides, the water vapor permeability of leathers may vary greatly with changing the temperature and relative humidity of the environment when the experiment is conducted. Because of the complexity of leathers and the uncertainty of affecting factors on the water vapor permeability of leathers, it is difficult to study the water vapor permeability of leathers and few studies are reported in the field.

In our previous works, the water vapor permeability of unfinished leather, polyurethane finished leather, filmed leather and synthetic leather was studied. The results showed that finishing plays an important role in affecting the water vapor permeability of leathers. Water vapor permeability of unfinished leather is far better than those of the other three samples. It was also found that the water vapor pressure difference between the two sides of the sample and the transferring action of hydrophilic groups on collagen chains are two main factors affecting the water vapor permeability for unfinished leathers. In cases of finished leather, filmed leather and synthetic leather, however, the mechanism of water vapor permeability is only the transporting of water molecules through capillaries in leathers, driven

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by the water vapor pressure difference between the two sides of the leather sample [5]. It was also found that the traditional processes of tanning, retanning, and fatliquoring may greatly affect the water vapor permeability of leathers [6,7].

Grey System Theory (GST) is a mathematic method. Different “colors” were used to describe whether the information is clear or not. “Black” indicates unknown or uncertain information, “white” indicates exact (or clear) information, and “grey” indicates partially clear and partially uncertain information. Through a series of theoretical analysis, grey system models (GSM) may be set up, and the unknown information may be obtained as a result. Since the emergence of Grey System Theory (GST), in only about 20 years, the Grey System Theory has been being improved rapidly and greatly. In the meantime, it has also been applied extensively and deeply in plenty of such fields as society, economy, science and technology, agriculture, industry, ecology, weather, petroleum, geology, hydrology, water resources, medicine, hygiene, securities, finance, and law, by systematic analysis, model establishing, and results predicting with great achievements [8-10]. However, few studies have been reported on the application of Grey System Theory in the field of leathers by now.

The Grey System Model was used to analyze and calculate the water vapor permeability of leathers. The system is made up from the physical structure parameters, chemical property parameters (i.e. groups on the collagen chains) and the water vapor permeability of leathers. The information is partially unknown and partially clear. At the same time, because the structure characteristic parameters and water vapor permeability may vary with different leathers, this system may be regarded as a Dynamic Grey System [11,12]. According to this theory, a Grey Model [GM] may be set up. Using the “white” information (clear or exact information) in the Grey System, the water vapor permeability of different leathers may be calculated immediately, conveniently and effectively. It may be helpful for us to know more about the water vapor permeability mechanism of leathers.

In this paper, Grey System Theory was used to investigate the water vapor permeability of leathers and the affecting factors. The Grey Model [GM(1,n)] has been set up, and four main factors including water-absorbing capacity, real density, thickness, and aperture ratio, that may affect the water vapor permeability of leathers were discussed. The results showed that the Grey System Theory may be used to study and calculate the water vapor permeability of leathers successfully.

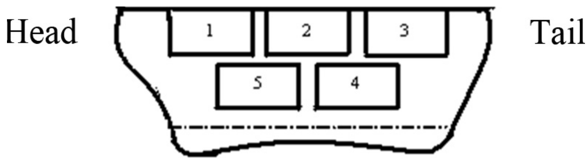

Fig. 1. Locations of samples cut from the sheepskin garment leather.

2. EXPERIMENTAL

2.1. Main materials and apparatus

Sodium chloride, analytically pure, and potassium chloride, chemically pure, were from Shanghai Chemical Reagent Co., Ltd, China. Urea, analytically pure, was from Luoyang Chemical Plant, China. Glucose and lactic acid, chemically pure, were from Zhengzhou Chemical Reagent Co., Ltd, China. Chemically pure and analytically pure are different grades of national reagent purity standards of China. The crust sheepskin garment leathers, which had not been finished, were provided by Heitianmingliang Leather-making Co. Ltd., China.

2.2. Preparation of leather samples

The crust sheepskin garment leather was divided and samples were taken according to Fig. 1 for the test.

2.3. Determination of the relative water vapor transmission ratio [13]

The relative water vapor transmission ratios of the samples were determined gravimetrically using a cup technique at 80 °C. The test sample was sealed to a metal cup containing distilled water, and the length between distilled water and the sample was controlled about 10 mm. The cup was put in a drying oven at 80 °C, and the weight of the sample, cup and distilled water was measured every 40 min for 7 times, the data were recorded as W_1, $W_2 \ldots W_i \ldots W_7$, respectively. A control test was also made, and the procedure was the same as mentioned above except that the cup wasn’t sealed with a leather sample. The data were also recorded as A_1, A_2, $A_3, \ldots, A_i, \ldots, A_7$, respectively. The relative water vapor transmission ratios (S) were then by Eq. (1):

$$S(\%) = \frac{W_i - W_{i-1}}{A_i - A_{i-1}} \times 100\%. \tag{1}$$

2.4. Determination of water vapor transmission ratio, aperture ratio, and water-absorbing capacity

The water vapor transmission ratio, aperture ratio, and water-absorbing capacity of the samples were determined according to the traditional method described in details in reference [14].

3. RESULTS AND DISCUSSION

3.1. GM (1,1) model and calculation of the water vapor permeability

GM (1,1) is a one-order Grey System Model with only one variable. The equation-composing technique used in the model to obtain the developing parameter "*a*" and the function variable "*u*", is fundamental in data fitting. It was believed that the given data should be fitted to a differential equation by the technique. The differential equation can be established by value differential coefficient formula, and the parameters of the differential equation can be calculated. The solution to the differential equation can be obtained by calculating the values of "*a*" and "*u*". And then, the predicted data can be obtained by the substitution technique. An example to calculate the water vapor permeability of unfinished sheepskin garment leathers at different time is described as follows.

The experimental data of relative water vapor permeability in different time are shown in Table 1. According to the technique of the GM (1,1), the water vapor permeability ratio of the samples form a sequence of number:

$$X^{(0)}(i) = [0.13 \;\; 0.25 \;\; 0.50 \;\; 0.60 \;\; 0.70 \;\; 0.78 \;\; 0.85], \tag{2}$$

where the data are the Relative Water Vapor Transmission Ratios (*S*)

(1) Transforming the original number sequence $X^{(0)}$ by *1—AGO*:

$$X^{(1)}(1) = X^{(0)}(1) = 0.13, \tag{3}$$

$$X^{(1)}(2) = X^{(0)}(1) + X^{(0)}(2) = 0.38, \tag{4}$$

$$X^{(1)}(3) = X^{(1)}(2) + X^{(0)}(3) = 0.88, \tag{5}$$

$$X^{(1)}(4) = X^{(1)}(3) + X^{(0)}(4) = 1.48, \tag{6}$$

$$X^{(1)}(5) = X^{(1)}(4) + X^{(0)}(5) = 2.18, \tag{7}$$

$$X^{(1)}(6) = X^{(1)}(5) + X^{(0)}(6) = 2.96, \tag{8}$$

$$X^{(1)}(7) = X^{(1)}(6) + X^{(0)}(7) = 3.81. \tag{9}$$

(2) Establishing the data matrix *B* and data vector y_N
From time function

$$\frac{\mathrm{d}X^{(1)}(t)}{\mathrm{d}t} + aX^{(1)}(t) = u \tag{10}$$

the following matrix may be established

$$B = \begin{pmatrix} -\frac{1}{2}\left(X^{(1)}(2)+X^{(1)}(1)\right) & 1 \\ -\frac{1}{2}\left(X^{(1)}(3)+X^{(1)}(2)\right) & 1 \\ \dots\dots\dots\dots & \\ -\frac{1}{2}\left(X^{(1)}(7)+X^{(1)}(6)\right) & 1 \end{pmatrix} = \begin{pmatrix} -0.255 & 1 \\ -0.630 & 1 \\ -1.180 & 1 \\ -1.830 & 1 \\ -2.570 & 1 \\ -3.385 & 1 \end{pmatrix}, \tag{11}$$

Table 1. Results* obtained from calculation by model and experimental about $X^{(0)}$.

Experimental	Calculation	Error
$X^{(0)}(2) = 0.25$	$\bar{X}^{(0)}(2) = 0.42$	$\varepsilon^{(0)}(2) = -0.17$
$X^{(0)}(3) = 0.50$	$\bar{X}^{(0)}(3) = 0.50$	$\varepsilon^{(0)}(3) = 0$
$X^{(0)}(4) = 0.60$	$\bar{X}^{(0)}(4) = 0.60$	$\varepsilon^{(0)}(4) = 0$
$X^{(0)}(5) = 0.70$	$\bar{X}^{(0)}(5) = 0.71$	$\varepsilon^{(0)}(5) = -0.01$
$X^{(0)}(6) = 0.78$	$\bar{X}^{(0)}(6) = 0.84$	$\varepsilon^{(0)}(6) = -0.06$
$X^{(0)}(7) = 0.85$	$\bar{X}^{(0)}(7) = 1.00$	$\varepsilon^{(0)}(7) = -0.15$

* where the data are the Relative Water Vapor Transmission Ratios (*S*).

$$Yn = \left[X^{(0)}(2) \;\; X^{(0)}(3) \;\; X^{(0)}(4) \;\; X^{(0)}(5) \;\; X^{(0)}(7) \right]^T = \left[0.25 \;\; 0.50 \;\; 0.60 \;\; 0.70 \;\; 0.78 \;\; 0.85 \right]^T. \tag{12}$$

(3) Calculating the value of B^TB

$$B^TB = \begin{pmatrix} -0.255 & -0.630 & -1.180 & -1.830 & -2.570 & -3.385 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} -0.255 & 1 \\ -0.630 & 1 \\ -1.180 & 1 \\ -1.830 & 1 \\ -2.570 & 1 \\ -3.387 & 1 \end{pmatrix} = \begin{pmatrix} 23.27 & -9.850 \\ -9.850 & 6 \end{pmatrix}. \tag{13}$$

(4) Calculating the *[B^TB]^-1*

$$\left[B^TB \right]^{-1} = \frac{1}{6 \times 23.27 - 9.85^2} \begin{pmatrix} 6 & 9.85 \\ 9.85 & 23.27 \end{pmatrix} = \begin{pmatrix} 0.141 & 0.231 \\ 0.231 & 0.546 \end{pmatrix}. \tag{14}$$

(5) Calculating the B^Ty_N

$$B^Ty_N = \begin{pmatrix} -0.255 & -0.630 & -1.180 & -1.180 & -2.570 & -3.385 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} 0.25 \\ 0.50 \\ 0.60 \\ 0.70 \\ 0.78 \\ 0.85 \end{pmatrix} = \begin{pmatrix} -7.250 \\ 3.680 \end{pmatrix}. \tag{15}$$

(6) Calculating ***a*** and ***u*** *by* the following matrix:

$$\vec{a} = \begin{bmatrix} a \\ u \end{bmatrix} = \left[B^TB \right]^{-1} B^TY_N = \begin{pmatrix} 0.141 & 0.231 \\ 0.231 & 0.546 \end{pmatrix} \begin{pmatrix} -7.250 \\ 3.680 \end{pmatrix} = \begin{pmatrix} -0.172 \\ 0.335 \end{pmatrix} \tag{16}$$

that is, a = -0.172, u = 0.335.

(7) Listing the differential equation:

$$\mathrm{d}X^{(1)}/\mathrm{d}t - ax^{(1)} = u. \tag{17}$$

Substituting the a and u in Eq. (17)

$$\mathrm{d}x^{(1)}/\mathrm{d}t - 0.172x^{(1)} = 0.335. \tag{18}$$

(8) Obtaining the time response function
Calculating the differential equation

$$\vec{X}^{(1)}(t+1) = 2.078e^{0.172t} - 1.948. \tag{19}$$

As $x^{(1)}(0) = x^{(0)}(1)$=0.13, then

$$\vec{X}^{(1)}(t+1) = 2.078e^{0.172t} - 1.948. \tag{20}$$

This is the water vapor permeability equation of the sheepskin garment leather samples studied here.

(9) Differentiating $\vec{X}^{(1)}(t+1)$

$$\vec{X}^{(0)}(t+1) = 0.357e^{0.172t}. \tag{21}$$

(10) Calculating the error by back substitution
Error can be obtained by the following equation:

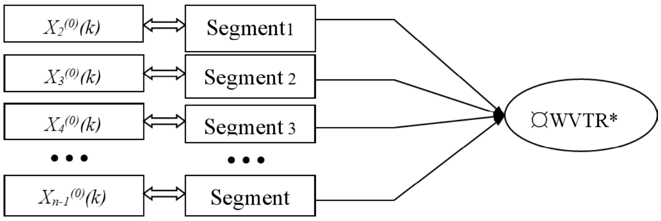

Fig. 2. Sketch of System Segments * Where WVTR is Water Vapor Transmission Ratio.

$$\varepsilon^{(1)}(t) = x^{(1)}(t) - \vec{X}^{(1)}(t) \quad t = 2,3,4,5,6,7, \qquad (22)$$

$$\varepsilon^{(0)}(t) = x^{(0)}(t) - \vec{X}^{(0)}(t) \quad t = 2,3,4,5,6,7. \qquad (23)$$

The Calculating results were obtained as shown in Table 1 and Table 2.

By scientific fitting, the water vapor permeability of the leather samples could be calculated. The work may serve as a reference in leather-making and leather goods making to get leather goods with good water vapor permeability.

The factors that affect the water vapor permeability of leathers may be classified into two fields. One is the structure parameters, including thickness, density and so on. The other is the feature parameters of leathers, such as the kinds of leathers (including hydrophilic groups on the collagen chains in the samples, the kind of leathers, and the leather chemicals used in leather making).

Some segments in the Grey System of the structure factors may affect the water vapor permeability of leathers (Fig. 2). The output is the WVTR (Water Vapor Transmission Ratio), noted as X_1. The inputs are represented as X_2~X_n. Fig. 2 shows the relationship among these data. The "*k*" in Fig. 2 represents the moment when the data were obtained. The experimental data at the moment of *k* (*k*=1~*m*) were dispersed by the time response. The superscript (0) shows that the data were the original experimental data and the subscripts (2, 3, 4… *n*-1) show the system variable orders (2, 3, 4… *n*-1). The water vapor permeability of the leather samples was grey, noted as ¤ in Fig. 2. Therefore, the white data was the water vapor transmission ratio of leathers. Both segments mentioned above were grey segments and the relationships among them were grey as well [8,9].

Table 2. Results* obtained from calculation by the model and experimental about $\vec{X}^{(1)}$.

Experimental	Calculation	Error
$X^{(1)}(2) = 0.38$	$\vec{X}^{(1)}(2) = 0.52$	$\varepsilon^{(1)}(2) = -0.14$
$X^{(1)}(3) = 0.88$	$\vec{X}^{(1)}(3) = 0.98$	$\varepsilon^{(1)}(3) = -0.10$
$X^{(1)}(4) = 1.48$	$\vec{X}^{(1)}(4) = 1.53$	$\varepsilon^{(1)}(4) = -0.05$
$X^{(1)}(5) = 2.18$	$\vec{X}^{(1)}(5) = 2.18$	$\varepsilon^{(1)}(5) = 0$
$X^{(1)}(6) = 2.96$	$\vec{X}^{(1)}(6) = 2.96$	$\varepsilon^{(1)}(6) = 0$
$X^{(1)}(7) = 3.81$	$\vec{X}^{(1)}(7) = 3.88$	$\varepsilon^{(1)}(7) = -0.07$

* where the data are the Relative Water Vapor Transmission Ratios (*S*).

Table 3. Experimental data for the analysis by *GM* (1,*n*)

Sample No.	1	2	3	4	5
WVTR* ($\times 10^{-3}$g/m^2•d), X_0	44.67	39.86	41.23	40.54	43.29
Water-absorbing Capacity (%), X_1	206.4	197.7	196.2	202.4	174.9
Real Density (g/cm^3), X_2	1.28	1.35	1.31	1.28	1.31
Thickness (mm), X_3	1.101	1.081	1.051	1.014	1.074
Aperture Ratio (%), X_4	34.78	35.16	39.32	34.00	44.82

* Where WVTR is Water Vapor Transmission Ratio.

3.2. Establishing of the Grey Model GM (1,n)

There are one output data and *n-1* input data in the grey system of water vapor permeability of leathers. The grey model *GM(1,n)* was established. The grey model *GM(1,n)* tells us the influences of the *n* variables on the first-order derivative of the dependent variable (variance ratio). So the *GM(1,n)* is a first order linear dynamic model of the *n* sequences.

According to the analysis of the experimental results, four factors were chosen as inputs in the study, which were water-absorbing capacity, real density, thickness, and aperture ratio, noted as X_1, X_2, X_3, and X_4, respectively. The water vapor permeability of leathers is the output, noted as X_0). Crust sheepskin garment leathers were tested to obtain the water vapor permeability. Table 3 shows all the inputs and output of the samples studied here.

In Table 3, every row may be regarded as a number sequence of and then five sequences were obtained.
(1) Transforming the original number sequence$X^{(0)}$ by *1—AGO*:

$$X_0^{(1)} = \begin{bmatrix} 44.67 & 84.53 & 125.8 & 166.3 & 209.6 \end{bmatrix}, \tag{24}$$

$$X_1^{(1)} = \begin{bmatrix} 206.4 & 404.1 & 600.3 & 802.7 & 977.6 \end{bmatrix}, \tag{25}$$

$$X_2^{(1)} = \begin{bmatrix} 1.280 & 2.630 & 3.940 & 5.220 & 6.530 \end{bmatrix}, \tag{26}$$

$$X_3^{(1)} = \begin{bmatrix} 1.101 & 2.182 & 3.233 & 4.247 & 5.321 \end{bmatrix}, \tag{27}$$

$$X_4^{(1)} = \begin{bmatrix} 34.78 & 69.94 & 109.3 & 143.3 & 188.1 \end{bmatrix}, \tag{28}$$

(2) Constructing data matrix B and data vector Y_N:

$$B = \begin{pmatrix} -\left[X_0^{(1)}(1) + X_0^{(1)}(2)\right]/2 & X_1^{(1)}(2) & X_2^{(1)}(2) & X_3^{(1)}(2) & X_4^{(1)}(2) \\ -\left[X_0^{(1)}(2) + X_0^{(1)}(3)\right]/2 & X_1^{(1)}(3) & X_2^{(1)}(3) & X_3^{(1)}(3) & X_4^{(1)}(3) \\ -\left[X_0^{(1)}(3) + X_0^{(1)}(4)\right]/2 & X_1^{(1)}(4) & X_2^{(1)}(4) & X_3^{(1)}(4) & X_4^{(1)}(4) \\ -\left[X_0^{(1)}(4) + X_0^{(1)}(5)\right]/2 & X_1^{(1)}(5) & X_2^{(1)}(5) & X_3^{(1)}(5) & X_4^{(1)}(5) \end{pmatrix} =$$

$$\begin{pmatrix} -64.600 & 404.100 & 2.630 & 2.182 & 69.640 \\ -105.145 & 600.300 & 3.940 & 3.233 & 109.260 \\ -146.300 & 802.740 & 5.220 & 4.247 & 143.260 \\ -187.945 & 977.630 & 6.530 & 5.321 & 188.080 \end{pmatrix}, \tag{29}$$

$$Y_N = \begin{bmatrix} 39.86 & 41.23 & 40.54 & 43.29 \end{bmatrix}^T . \tag{30}$$

(3) Establishing the differential equation:

$$\mathrm{d}X_0^{(1)} / \mathrm{d}t + aX_0^{(1)} = b_1 X_1^{(1)} + b_2 X_2^{(1)} + ... + b_4 X_4^{(1)} . \tag{31}$$

(4) Coefficient vector:

$$\vec{a} = \begin{bmatrix} a & b_1 & b_2 & b_3 & b_4 \end{bmatrix}^T . \tag{32}$$

(5) Calculating the solution by least-squares procedure:

$$\vec{a} = \left(B^T B\right)^{-1} B^T Y_N , \tag{33}$$

where B is an accumulative matrix, and Y_N is a constant vector.
The following matrix can be obtained:

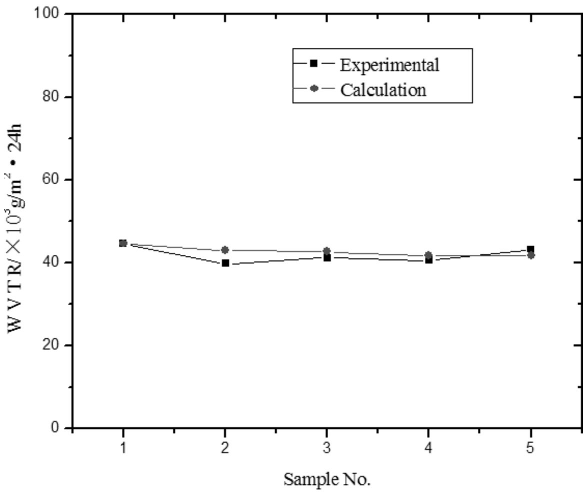

Fig. 3. Calculation and experimental WVTR of the samples (where WVTR is Water Vapor Transmission Ratio).

$$\vec{a} = \begin{pmatrix} 1.824 \\ 0.161 \\ 13.94 \\ 15.96 \\ 0.285 \end{pmatrix}. \tag{34}$$

And the following data may be obtained: $a = 1.824$, $b_1 = 0.161$, $b_2 = 13.94$, $b_3 = 15.96$, $b_4 = 0.285$

The differential equation of *GM(1, 5)* is:

$$\frac{dx_0^{(1)}}{dt} + 1.824X_0^{(1)} = 0.161X_1^{(1)} + 13.94X_2^{(1)} + 15.96X_3^{(1)} + 0.285X_4^{(1)}. \tag{35}$$

The solution to the differential equation is:

$$X_0^{(1)}(t+1) = \left[X_0^{(0)}(1) - \sum_{i=1}^{4} \frac{b_{i-1}}{a} X_i^{(1)}(t+1) \right] e^{-at} + \sum_{i=1}^{4} \frac{b_{i-1}}{a} X_i^{(1)}(t+1). \tag{36}$$

The grey equation can be obtained by substituting the parameters of sample N_1:

$$X_0^{(1)}(t+1) = \left[44.67 - \left(0.088X_1 + 7.643X_2 + 8.748X_3 + 0.156X_4\right)\right]e^{-1.824t} + \left(0.088X_1 + 7.643X_2 + 8.748X_3 + 0.156X_4\right). \tag{37}$$

Using the equation, the calculated results were obtained as shown in Table 4 and Fig. 3. The experimental data were also shown in Table 4 and Fig. 3.

From Table 4 and Fig. 3, it was found that there is an ideal correlation between the calculated data by grey analysis and the experimental data. So the calculation is reliable. By testing the values mentioned above (such as water-absorbing capacity) which are easy to be obtained, the water vapor permeability of large quantities of leathers that need to be obtained in a long time may be obtained in a short time. And this does good to control and to test the water vapor permeability of leathers. Besides, by calculating the water vapor permeability, we know that there is a cooperative effect among the affecting factors on the water vapor permeability of leathers. If more structural parameters are determined and fitted, we may obtain more exact grey system equations. If the materials and fiber woven characteristics of leathers can be quantified as parameters for the grey model, the applicability of the model could be improved greatly.

3.3. Grey relevancy analysis of the affecting factors of water vapor permeability

From the analysis mentioned above, because many factors may affect the water vapor permeability of leathers, some questions may arise and need to be solved in order to improve the water vapor permeability of leathers: Which are the main factors and which are less important? Which contribute more to the water vapor permeability and which contribute

Table 4. *GM (1,5)* Calculation and Experimental of WVTR*.

Sample No.	2	3	4	5
Calculation	42.98	42.60	41.78	41.79
Experimental	39.86	41.23	40.54	43.29
Error	-3.12	-1.37	-1.24	1.50
Relative error%	-7.3%	-3.4%	-3.0%	3.6%

* Where WVTR is Water Vapor Transmission Ratio.

less? Which need to be strengthened and which need to be weakened to get leathers with reasonable water vapor permeability? By putting the research results into use, leathers can be produced with ideal water vapor permeability by appropriately controlling the factors in leather-making.

In this paper, four such factors as water-absorbing capacity (X_1), real density (X_2), thickness (X_3), and aperture ratio (X_4), were chosen and applied in the study. The experimental data are shown in Table 3, on the basis of which the grey relevant analysis was done.

3.3.1. Absolute relevancy coefficient

Using the data in Table 3, grey relevancy analysis was done as follows.
Suppose

$$X_i^0 = [x_i(1) - x_i(1) \quad x_i(2) - x_i(1) \quad x_i(3) - x_i(1) \quad x_i(4) - x_i(1) \quad x_i(5) - x_i(1)] = [x_i^0(1) \quad x_i^0(2) \quad x_i^0(3) \quad x_i^0(4) \quad x_i^0(5)]. \quad (38)$$

The following number sequences were obtained:

$$X_0^0 = [0 \quad -4810 \quad -3436 \quad -4123 \quad -1374], \quad (39)$$

$$X_1^0 = [0 \quad -8.64 \quad -10.16 \quad -3.92 \quad -31.47], \quad (40)$$

$$X_2^0 = [0 \quad 0.07 \quad 0.03 \quad 0 \quad 0.03], \quad (41)$$

$$X_3^0 = [0 \quad -0.02 \quad -0.05 \quad -0.087 \quad -0.03], \quad (42)$$

$$X_4^0 = [0 \quad 0.38 \quad 4.54 \quad -0.78 \quad 10.04], \quad (43)$$

and

$$|s_i| = \left|\sum_2^4 x_i^0(k) + \frac{1}{2}x_i^0(5)\right|; \quad i = 0,1,2,3,4, \quad (44)$$

$|s_0|$ = 1.306*10^4, $|s_1|$ = 38.435, $|s_2|$ = 0.115, $|s_3|$ = 0.171, $|s_4|$ = 9.160,
and

$$|s_i - s_0| = \left|\sum_2^4 \left(x_i^0(k) - x_0^0(k)\right) + ; \frac{1}{2}\left(x_i^0(5) - x_0^0(5)\right)\right| \; i = 1,2,3,4, \quad (45)$$

$|s_1 - s_0|$ = 1.302*10^4, $|s_2 - s_0|$=1.306*10^4, $|s_3 - s_0|$=1.306*10^4, $|s_4 - s_0|$= 1.307*10^4
And from

$$\varepsilon_{0i} = \frac{1 + |s_0| + |s_i|}{1 + |s_0| + |s_i| + |s_i - s_0|} \quad i = 1,2,3,4. \quad (46)$$

The following was obtained.
ε_{01} =0.501, ε_{02} =0.333, ε_{03} =0.250, ε_{04}=0.200

3.3.3 Relative relevancy coefficients

Calculating the initial value image of X_i (i =0, 1, 2, 3, 4)

$$X_i' = [x_i'(1), x_i'(2), x_i'(3), x_i'(4), x_i'(5)] = \left(\frac{x_i(1)}{x_i(1)}, \frac{x_i(2)}{x_i(1)}, \frac{x_i(3)}{x_i(1)}, \frac{x_i(4)}{x_i(1)}, \frac{x_i(5)}{x_i(1)}\right) \quad (47)$$

$i = 0,1,2,3,4,$

which is:

$$X_0' = [1.000 \quad 0.892 \quad 0.923 \quad 0.908 \quad 0.970], \quad (48)$$

$$X_1' = [1.000 \quad 0.958 \quad 0.951 \quad 0.981 \quad 0.848], \quad (49)$$

$$X_2' = [1.000 \quad 1.055 \quad 1.023 \quad 1.000 \quad 1.023], \quad (50)$$

$$X_3' = [1.000 \quad 0.982 \quad 0.955 \quad 0.921 \quad 0.976], \quad (51)$$

$$X_4' = [1.000 \quad 1.011 \quad 1.131 \quad 0.978 \quad 1.289], \quad (52)$$

Calculating the original cipher image of X_i' (i = 0,1,2,3,4) :

$$X_i'^0 = [x_i'^0(1) \quad x_i'^0(2) \quad x_i'^0(3) \quad x_i'^0(4) \quad x_i'^0(5)] = [x_i'^0(1) - x_i'^0(1) \quad x_i'^0(2) - x_i'^0(1) \quad x_i'^0(3) - x_i'^0(1) \quad x_i'^0(4) - x_i'^0(1) \quad x_i'^0(5) - x_i'^0(1)] \quad (53)$$

$$X_0'^0 = [0 \quad -0.108 \quad -0.077 \quad -0.092 \quad -0.031], \quad (54)$$

$$X_1'^0 = [0 \quad -0.042 \quad -0.049 \quad -0.019 \quad -0.153], \quad (55)$$

$$X_2'^0 = [0 \quad 0.055 \quad 0.023 \quad 0 \quad 0.023], \quad (56)$$

$$X_3'^0 = [0 \quad -0.018 \quad -0.045 \quad -0.079 \quad -0.025], \quad (57)$$

$$X_4'^0 = [0 \quad 0.011 \quad 0.131 \quad -0.022 \quad 0.289], \quad (58)$$

From

$$|s_i'| = \left|\sum_2^4 x_i'^0(k) + \frac{1}{2}x_i'^0(5)\right|; \quad i = 0,1,2,3,4, \quad (59)$$

$$\left|s_i' - s_0'\right| = \left|\sum_2^4 \left(x_i'^0(k) - x_0'^0(k)\right) + \frac{1}{2}\left(x_i'^0(5) - x_0'^0(5)\right)\right|; \; i = 1,2,3,4. \tag{60}$$

The following results were obtained:
$|s_0'|$=0.292, $|s_1'|$=0.186, $|s_2'|$=0.090, $|s_3'|$=0.155, $|s_4'|$=0.263
$|s_1'-s_0'|$ =0.106, $|s_2'-s_0'|$ =0.382, $|s_3'-s_0'|$ =0.138, $|s_4'-s_0'|$=0.556
From

$$r_{0i} = \frac{1+\left|s_0'\right|+\left|s_i'\right|}{1+\left|s_0'\right|+\left|s_i'\right|+\left|s_i'-s_0'\right|}; \; i = 1,2,3,4 \tag{61}$$

The following was obtained:
r_{01} = 0.933, r_{02} = 0.783, r_{03} = 0.913, r_{04} = 0.737.

3.3.4. Integrated relevancy coefficient

According to grey relevancy analysis theory,

$$\rho_{0i} = \theta\varepsilon_{0i} + (1-\theta) r_{0i},$$

where ρ_{0i} is the grey integrated relevancy coefficient. In general, θ is 0.5. If paying more attention to the relationship among absolute quantities, we know that θ may be a little higher. When we pay more attention to the changing ratios, θ may be a little smaller. In this paper, θ is fixed as 0.5 [12].

As

$$\rho_{0i} = \theta\varepsilon_{0i} + (1-\theta) r_{0i}, \; i = 1,2,3,4,$$

The following results were obtained:
ρ_{01} = 0.71, ρ_{02} = 0.56, ρ_{03} = 0.58, ρ_{04} = 0.47.

3.3.5. Results analysis

Because

$$\rho_{01} > \rho_{02} > \rho_{03} > \rho_{04}, \tag{62}$$

The contribution of the four affecting factors to the water permeability of leathers ranks as

$$X_1 > X_2 > X_3 > X_4. \tag{63}$$

It is to say that the contribution to the water vapor permeability from the four affecting factors studied here ranks as

Water-absorbing capacity > thickness > real density > aperture ratio

The results indicate that water-absorbing capacity is the most important factor affecting the water vapor permeability of leathers. In other words, among the four affecting factors studied here, water-absorbing capacity affects the water vapor permeability of leathers the mostly. The next comes the thickness of the samples. Comparatively speaking, the contributions to the water vapor permeability from the real density and aperture ratio are really less. Therefore, in order to improve the water permeability of leathers, the most efficient way is trying to increase the water-absorbing capacity of leathers. It's better to choose leather chemicals with polar group to increase the water affinity of the collagen fibers in leather-making. The results could also be guidance in choosing leather materials (such as shoe or garment with good water vapor permeability). For example, thin leather usually has advantages of providing high water vapor permeability. As finishing plays an important role in water vapor permeability, in order to improve the water vapor permeability of leathers, studies should be done on how to improve the water absorbing capacity of finishing agent. On the other hand, if the water absorbing capacity of finishing agent is too high, the wet rubbing resistance may be decreased. So the work should be done to find a balance in improve the water absorbing capacity without decreasing the wet rubbing resistance of leathers.

4. CONCLUSIONS

Some equations about the time test of the water vapor permeability of leathers were obtained by computer calculation. These equations may tell us the water vapor permeability of leathers successfully and to help us know the water vapor permeability mechanism of the leathers. It may also help us choose leather chemicals to make leathers with improved water vapor permeability.

By applying the Grey System Theory to analyze the original data of the affecting factors, the contributions of the four factors studied here on water vapor permeability were found as follows:

Water-absorbing capacity > thickness > real density > aperture ratio

Water-absorbing capacity is the most important factor, which may significantly affect the water vapor permeability of leathers, while thickness comes the second. Less effect was found from real density and aperture ratio on the water vapor permeability is found. In order to improve the water vapor permeability of leathers, it should be done to increase the water absorbing capacity of leathers.

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