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Research Article

Reliability Analysis of Toughened Vacuum Glass Based on Gray Relation Decision

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The gray system theory was introduced in the design of toughened vacuum glass, and an evaluation mathematical model based on improved gray correlation was established. According to the service performance index of tempered vacuum glass, determine the index system of product evaluation. Based on the improved gray absolute correlation method, the module vacuum glass was analyzed and calculated. The weight of each evaluation index is obtained according to the deviation matrix, and the relevance of the sample data line to the reference data line is elaborated from the perspective of proximity and thus combined with the weight of each evaluation index to get the comprehensive gray correlation. The results of the trial design scheme are designed to prove its effectiveness in vacuum glass product quality evaluation and feasibility.

1. Introduction

Normal glass will form a permanent stress during annealing cooling [1], and the strength will also decrease. Ordinary glass is subjected to deep processing, and the strength of the glass is gradually increased to form tempered glass [2]. Ordinary vacuum glass, with a low heat transfer coefficient, has a good effect of isolating sound transmission, but its carrying capacity is not as good as tempered glass [3, 4]. Tempered vacuum glass replaces ordinary vacuum glass with tempered glass, which is a new type of energy-saving transparent insulation material. The principle is similar to a thermos, with excellent insulation heat transfer performance, sound insulation performance, and antiwind pressure performance. After the damage, the tempered glass does not cause a large area to fall off, but the formation of irregular shape of small particles. Therefore, tempered vacuum glass is called safe type glass [5–9]. Its emergence which prompted the vacuum glass industry to the technical, energy-saving direction is the world's glass processing technology research hotspot [10].

In the quality evaluation of toughened vacuum glass product, it is necessary to conduct an evaluation study on the performance quality of the tempered vacuum glass product and the combined working environment conditions [11]. The factors that affect the quality of vacuum glass are diverse and complex. For example, the position and number of supports in tempered vacuum glass will affect the applicability of the glass, making the evaluation result lack objectivity and accuracy [12–14]. The gray system theory mainly studies how to solve the uncertainty problem of 'small sample' or 'lack of relevant information.' Based on the information coverage, the reality of the movement of things is explored through the role of sequence operators [15, 16].

In view of the uncertainty of vacuum glass quality evaluation factors, the gray system theory was introduced in the quality evaluation process. Quality performance indicators of vacuum glass establish a quality evaluation system for vacuum glass based on the improved gray correlation method, conduct a comprehensive evaluation, and get objective evaluation results.

2. Establishing the Comprehensive Evaluation Mathematical Model of Improved Gray Correlation Method

One of the important methods for studying and dealing with complex systems with gray system theory is gray correlation analysis [17, 18]. This method has no excessive requirements on the number of samples, thus making up for the lack of sample size in vacuum glass quality evaluation. Only a small sample size can be used for correlation analysis.

Gray correlation method is a branch of gray system theory. This is a theory that studies and deals with complex systems starting from the incompleteness of information. Gray relational method is often used as a comprehensive evaluation method of multi-index system [19]. Generally, the optimal scheme is selected as the standard sequence, and the scheme with the largest degree of association is the best.

In general, the correlation coefficients in the gray correlation analysis are fixed values. The resolution coefficient value is generally set to 0.5, and the value cannot be adjusted reasonably according to the application. Appropriate resolution coefficients can fully reflect the integrity of the relevance, while weakening the impact of outliers on the associated space. This study proposes a mathematical model of relevance that is based on the gray system and improved on this basis. Its principle is to make the number of data uniform by interval value.

2.1. Establishment of Behavior Index Sequence. In the study of behavior factor X_0 in a certain aspect, the method of identifying the influence on X_0 by using multiple factors x_i $(i = 1, 2, \ldots, m)$ is called grey relational analysis. The quality of tempered vacuum glass and its service life depend on the combined effects of various factors.

The tempered vacuum glass is the research object. Introducing the quality influencing factors into the concept of behavioral factors, the vacuum glass evaluation index X_0 systematic behavior index sequence is

$$X_0 = \{x_0(1), x_0(2), \cdots, x_0(k), \cdots, x_0(n)\} \tag{1}$$

$x_0(k)$ is the k rating data of a certain behavior factor of the reliability of toughened vacuum glass.

Assume that there are a total of m factors that affect the reliability of the product. Data is extracted through relevant experiments. The sequence of the sample behavioral index that obtained the i th factor $(i < m)$ influencing factor x_i is

$$X_i = \{x_i(1), x_i(2), \cdots, x_i(k), \cdots, x_i(n)\} \tag{2}$$

i represents the i influencing factor number, i=1,2,. . .,m. k is data serial number k=1,2,. . .,n. $x_i(k)$ represent the k th measurement of the influencing factor x_i.

2.2. Interval-Value Processing. Before performing correlation analysis, first select the interval-value method to deal with the sample data. In formula (2), the interval-valued operator Z is introduced:

$$X_iZ = \{x_i(1)z, x_i(2)z, \cdots, x_i(k)z, \cdots x_i(n)z\} \tag{3}$$

$x_i(k)$z in formula (3) is as follows:

$$x_i(k)z = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \tag{4}$$

According to formula (3), formula (4) quoted interval operator Z, and the interval value processing of behavioral feature sequences is carried out, resulting in the processed data sequence, marked as $X'_0, X'_1, X'_2, \ldots, X'_m$.

2.3. Difference Sequence and Range. Derived from the new series of intervalization, the four axioms of gray correlation are derived as follows:

$$\Delta_i(k) = \left|x'_0(k) - x'_i(k)\right| \tag{5}$$

$$\Delta_i = (\Delta_i(1), \Delta_i(2), \cdots, \Delta_i(n)) \tag{6}$$

According to (5) and (6), the difference data sequence is obtained. The range of extreme differences to find out the maximum and minimum of each group difference sequence is as follows:

$$\Delta_{\max} = \max_i \max_k \Delta_i(k) \tag{7}$$

$$\Delta_{\min} = \min_i \min_k \Delta_i(k) \tag{8}$$

2.4. Correlation Coefficient Sequence and Correlation Degree. Equations (1) and (2) show the system behavior signature sequence and sample behavior sequence, and definition ρ is the resolution coefficient $\rho \epsilon [0, 1]$.

$$\gamma(X_0(k), X_i(k)) = \frac{\min_i \min_k |x_0(k) - x_i(k)| + \rho \max_i \max_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho \max_i \max_k |x_0(k) - x_i(k)|} \tag{9}$$

$$\gamma(X_0, X_i) = \frac{1}{n}\sum_{k=1}^{n} \gamma(X_0(k), X_i(k)) \tag{10}$$

Given the gray correlation coefficient sequence of $\gamma(X_0(k),X_i(k))$, if the coefficient $\gamma(X_0,X_i)$ satisfies the gray relational four axioms, then it is called the gray relational degree of X_i to X_0.

The value of the resolution coefficient ρ in formula (9) is as follows.

Δ_v is the mean of all absolute differences:

$$\Delta_v = \frac{1}{m \cdot n}\sum_{i=1}^{m}\sum_{k=1}^{n} |x_0(k) - x_i(k)| \tag{11}$$

marked as

$$\varepsilon_\Delta = \frac{\Delta_v}{\Delta_{\max}} \tag{12}$$

When $\Delta_{max} > 3\Delta_v$, ρ value range is formula (13). When $\Delta_{max} \leq 3\Delta_v$, ρ value range is formula (14), as follows:

$$\varepsilon_\Delta \leq \rho \leq 1.5\varepsilon_\Delta \tag{13}$$

$$1.5\varepsilon_\Delta < \rho \leq 2\varepsilon_\Delta \tag{14}$$

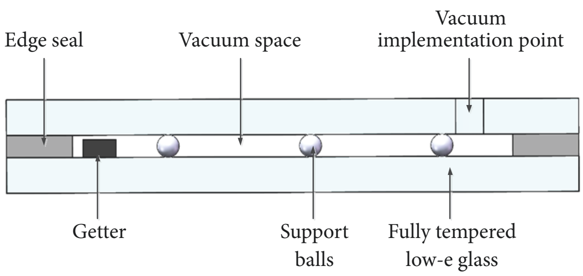

Figure 1: Tempered vacuum glass cross section composition.

3. Dependability of the Module Division and Determine the Sample Module

3.1. Determination of the Reliability of Toughened Vacuum Glass. Tempered vacuum glass is a new type of energy-saving glass. It is composed of two pieces of tempered glass, and the glass plates are separated by a fixed array arrangement with a height of 0.1~0.2mm. Tempered glass is used around the glass for low temperature sealing. Open a suction hole in one of the glass panes for vacuum exhaust (Figure 1).

According to the actual investigation of the enterprise, 20 factors of the tempered vacuum glass product structure were determined. The impact factors were screened from the module of the reliability index characteristics category and design requirements. From the point of view of reliability and actual production, 20 influencing factors were optimized and screened, and 15 of them were selected as evaluation indexes. At the same time, the whole structure of the tempered vacuum glass is divided into three major modules: the glass airtight property module, the glass substrate property module, and the support preferred module. The glass gas seal module contains a vacuum suction device, getter, and airtight properties. The main issue is the hermeticity of tempered vacuum glass. In the process of sealing and evacuating the glass, if it is handled improperly, no vacuum environment can be formed inside the glass cavity. It makes the tempered vacuum glass unable to play the role of insulation and sound insulation. The glass substrate characteristics module includes the impact resistance and corrosion resistance of the glass substrate itself. The preferred support module relates to various parameters of the support, including size, shape, material, and the like. The reliability indexes and contents contained in each module are shown in Table 1. The contents of the indicator parameters are slightly different according to different design requirements.

3.2. Evaluation of Reliability Index Parameters. The tempered vacuum glass samples were evaluated based on these 15 reliability evaluation indicators. According to the characteristics of glass seal, the vacuum coefficient inspection equipment was used for sampling inspection. According to the characteristics of glass, it is evaluated according to the production equipment and production process. It needs to be evaluated according to the performance of the application and the relevant data obtained by the company for different customer needs.

Table 1: Reliability index of toughened vacuum glass.

Symbol	Reliability indicators	Include
$X_0(1)$	tightness	glass cavity vacuum degree
		extractor vent size
$X_0(2)$	getter performance	getter service time
$X_0(3)$	strength sealing	service time
$X_0(4)$	compressive properties	sealing parts of the compression capacity
$X_0(5)$	impact resistance	sealing at external shock resistance
$X_0(6)$	production temperature control	low temperature production of tempered glass
$X_0(7)$	glass strength stiffness	tempered glass quality
$X_0(8)$	glass surface impact resistance	impact resistance of external substrates on glass substrates
$X_0(9)$	corrosion resistance of glass surface	glass surface features such as rainwater corrosion
$X_0(10)$	glass substrate explosion-proof characteristics	lightfastness to glass properties
$X_0(11)$	support strength characteristics	support pressure characteristics
$X_0(12)$	support placement spacing	patch space size
$X_0(13)$	support diameter size	0.4~0.6mm
$X_0(14)$	support material for production	steel, ceramics
$X_0(15)$	support shape style	rings, spheres

Table 2: Evaluation of the basis of division.

satisfy the performance percentage	assessment level	Assessment factors
120%~140%	excellent	8~10
100%~120%	well	6~8
80%~100%	poor	4~6
<80%	worst	0~4

The reliability index and index parameter in Table 1 are used as the basis for evaluating the evaluation coefficient of product test samples. According to the test sample reliability index and relative to the performance of the original index performance, the assessment of the reliability indicators for tempered vacuum glass is divided into five categories, Table 2.

According to the existing sample parameters, evaluation rules, and partition modules, the index sequence of system characteristic behavior is obtained. The 15 reliability indexes were tested and evaluated.

$$X_0 = \{8, 7, 9, 9, 8, 7, 8, 7, 7, 7, 7, 8, 6, 6, 8\} \tag{15}$$

3.3. Determine the Sample of Assessment Data. According to different application fields of tempered vacuum glass, such as environmental temperature requirements and size parameters, a large number of representative data samples are needed. From the existing tempered vacuum glass data samples, 12 sets of test samples with different design ideas and representative structures or functions were randomly selected. According to the established module classification and evaluation rules, 12 kinds of prototypes were tested for reliability index evaluation.

$$\begin{aligned}
X_1 &= \{8.7, 6.8, 9.1, 8.8, 8.5, 7.6, 8.2, 7.2, 6.9, 7.4, 7.3, 8.5, 6.2, 6.7, 8.8\}\\
X_2 &= \{8.3, 7.2, 9.2, 9.4, 8.7, 7.1, 8.3, 6.8, 7.2, 7.8, 7.6, 8.7, 6.6, 6.7, 8.7\}\\
X_3 &= \{7.9, 7.1, 9.3, 9.3, 7.9, 7.3, 7.7, 7.1, 7.7, 7.6, 6.9, 8.5, 6.6, 6.5, 8.2\}\\
X_4 &= \{8.3, 7.4, 9.2, 8.8, 8.2, 7.2, 7.9, 7.1, 7.3, 7.2, 7.2, 8.2, 6.7, 6.4, 7.9\}\\
X_5 &= \{8.6, 7.7, 9.7, 9.2, 8.1, 7.7, 8.7, 7.1, 7.4, 7.2, 7.2, 8.3, 6.2, 6.1, 8.9\}\\
X_6 &= \{8.3, 7.8, 9.7, 9.6, 7.3, 7.6, 8.1, 7.4, 7.6, 7.7, 7.2, 7.6, 6.8, 6.4, 8.4\}\\
X_7 &= \{8.9, 7.0, 9.3, 8.4, 7.6, 6.7, 8.2, 7.1, 7.1, 7.3, 7.2, 8.7, 6.0, 6.9, 8.5\}\\
X_8 &= \{8.7, 7.3, 9.7, 9.8, 8.1, 6.8, 8.0, 7.2, 7.6, 7.8, 6.3, 8.4, 6.9, 6.5, 8.3\}\\
X_9 &= \{8.3, 7.1, 9.0, 9.9, 8.7, 7.4, 8.2, 7.4, 7.7, 7.4, 7.6, 7.9, 6.3, 6.2, 7.8\}\\
X_{10} &= \{8.6, 7.3, 9.1, 9.1, 8.2, 7.3, 8.5, 7.4, 7.0, 7.4, 7.2, 7.8, 6.2, 6.6, 7.8\}\\
X_{11} &= \{8.2, 7.8, 9.1, 9.5, 8.1, 7.3, 8.5, 7.8, 7.2, 7.7, 7.1, 8.2, 6.2, 6.4, 8.0\}\\
X_{12} &= \{8.3, 7.2, 9.6, 9.0, 8.4, 7.2, 7.7, 7.4, 7.9, 7.5, 7.3, 8.2, 6.4, 6.5, 7.9\}
\end{aligned} \tag{16}$$

As a result, preliminary evaluation data samples of tempered vacuum glass reliability have been obtained.

4. Reliability Gray Correlation Analysis of Modular Tempered Vacuum Glass

After constructing systematic behavioral index sequence and behavioral index sequence, it is applied in established mathematical model of gray correlation degree. The module is optimized for design and the product design for tempered vacuum glass is completed.

4.1. Gray Relational Analysis of Glass Airtightness Module. The results were evaluated based on the reliability index of the glass seal parameters, the sequence of behaviors of the 12 groups of prototypes is as follows:

$$\begin{aligned}
X_1 &= \{8.7, 6.8, 9.1, 8.8, 8.5, 7.6\}\\
X_2 &= \{8.3, 7.2, 9.2, 9.4, 8.7, 7.1\}\\
X_3 &= \{7.9, 7.1, 9.3, 9.3, 7.9, 7.3\}\\
X_4 &= \{8.3, 7.4, 9.2, 8.8, 8.2, 7.2\}\\
X_5 &= \{8.6, 7.7, 9.7, 9.2, 8.1, 7.7\}\\
X_6 &= \{8.3, 7.8, 9.7, 9.6, 7.3, 7.6\}\\
X_7 &= \{8.9, 7.0, 9.3, 8.4, 7.6, 6.7\}\\
X_8 &= \{8.7, 7.3, 9.7, 9.8, 8.1, 6.8\}\\
X_9 &= \{8.3, 7.1, 9.0, 9.9, 8.7, 7.4\}\\
X_{10} &= \{8.6, 7.3, 9.1, 9.1, 8.2, 7.3\}\\
X_{11} &= \{8.2, 7.8, 9.1, 9.5, 8.1, 7.3\}\\
X_{12} &= \{8.3, 7.2, 9.6, 9.0, 8.4, 7.2\}
\end{aligned} \tag{17}$$

Before performing the gray correlation analysis, the interval operator Z is first quoted according to formula (3) and formula (4). The 13 groups of behavioral feature sequences are interval-valued. Obtain the interval-valued data sequence (reserve 2 significant digits). Record them as $X_0', X_1', X_2',\ldots,X_{10}'$ as follows:

$$\begin{aligned}
X_0' &= \{0.67, 0.33, 1.00, 1.00, 0.67, 0.33\}\\
X_1' &= \{0.86, 0.21, 0.93, 0.90, 0.79, 0.48\}\\
X_2' &= \{0.61, 0.21, 1.00, 1.00, 0.75, 0.18\}\\
X_3' &= \{0.50, 0.21, 1.00, 1.00, 0.50, 0.29\}\\
X_4' &= \{0.68, 0.36, 1.00, 0.86, 0.64, 0.29\}\\
X_5' &= \{0.69, 0.44, 1.00, 0.86, 0.56, 0.44\}\\
X_6' &= \{0.58, 0.42, 1.00, 0.97, 0.27, 0.36\}\\
X_7' &= \{0.88, 0.30, 1.00, 0.73, 0.48, 0.21\}\\
X_8' &= \{0.69, 0.29, 0.97, 1.00, 0.51, 0.14\}\\
X_9' &= \{0.57, 0.24, 0.76, 1.00, 0.95, 0.32\}\\
X_{10}' &= \{0.73, 0.33, 0.88, 1.00, 0.61, 0.33\}\\
X_{11}' &= \{0.61, 0.48, 0.88, 1.00, 0.58, 0.33\}\\
X_{12}' &= \{0.59, 0.25, 1.00, 0.81, 0.63, 0.25\}
\end{aligned} \tag{18}$$

Table 3: Range of difference sequence.

sequence	max	min
Δ_1	0.19	0
Δ_2	0.15	0
Δ_3	0.17	0
Δ_4	0.14	0
Δ_5	0.14	0
Δ_6	0.40	0
Δ_7	0.27	0
Δ_8	0.19	0
Δ_9	0.28	0
Δ_{10}	0.12	0
Δ_{11}	0.15	0
Δ_{12}	0.19	0

Table 4: Glass hermetic features module gray correlation.

sequence	gray relational degree
γ_{01}	0.668
γ_{02}	0.737
γ_{03}	0.723
γ_{04}	0.851
γ_{05}	0.741
γ_{06}	0.742
γ_{07}	0.655
γ_{08}	0.78
γ_{09}	0.697
γ_{010}	0.862
γ_{011}	0.777
γ_{012}	0.745

The results of the compartmentalization are sorted out, and 13 new sequences are listed. According to formula (5) and formula (6), the difference data sequence is obtained.

$$\begin{aligned}
\Delta_1 &= \{0.19, 0.12, 0.00, 0.10, 0.12, 0.15\} \\
\Delta_2 &= \{0.06, 0.12, 0.07, 0.00, 0.08, 0.15\} \\
\Delta_3 &= \{0.17, 0.12, 0.00, 0.00, 0.17, 0.04\} \\
\Delta_4 &= \{0.01, 0.03, 0.00, 0.14, 0.03, 0.04\} \\
\Delta_5 &= \{0.02, 0.11, 0.00, 0.14, 0.11, 0.11\} \\
\Delta_6 &= \{0.09, 0.09, 0.00, 0.03, 0.40, 0.03\} \\
\Delta_7 &= \{0.21, 0.03, 0.00, 0.27, 0.19, 0.12\} \\
\Delta_8 &= \{0.02, 0.04, 0.03, 0.00, 0.16, 0.19\} \\
\Delta_9 &= \{0.10, 0.09, 0.24, 0.00, 0.28, 0.01\} \\
\Delta_{10} &= \{0.06, 0.00, 0.12, 0.00, 0.06, 0.00\} \\
\Delta_{11} &= \{0.06, 0.15, 0.12, 0.00, 0.09, 0.00\} \\
\Delta_{12} &= \{0.08, 0.08, 0.00, 0.19, 0.04, 0.08\}
\end{aligned} \tag{19}$$

According to formula (7) and formula (8) for data retrieval, find out the value of each group. Among them, the results of maximum and minimum of the i-th corresponding Δ_i sequence are listed in Table 3.

As shown in Table 3, Δ_{max}=0.40, Δ_{min}=0.

Begin to calculate the gray correlation coefficient sequence and the gray correlation degree. First, follow calculations according to (9) and (10) and rewrite the formula for the gray correlation coefficient as

$$\gamma_{0i}(k) = \frac{\Delta_{min} + \rho\Delta_{max}}{\Delta_i(k) + \rho\Delta_{max}} \tag{20}$$

From formula (20), the gray correlation coefficient sequence β_{0i} and the gray correlation degree γ_{0i} are derived as follows:

$$\beta_{0i} = \{\gamma_{0i}(1), \gamma_{0i}(2), \cdots, \gamma_{0i}(k), \cdots, \gamma_{0i}(n)\} \tag{21}$$

$$\gamma_{0i} = \frac{1}{n}\sum_{k=1}^{n}\beta_{0i} \tag{22}$$

Through the above formula, the coefficient of gray correlation can be calculated.

$$\begin{aligned}
\beta_{01} &= \{0.51, 0.63, 1.00, 0.67, 0.63, 0.57\} \\
\beta_{02} &= \{0.77, 0.63, 0.74, 1.00, 0.71, 0.57\} \\
\beta_{03} &= \{0.54, 0.63, 1.00, 1.00, 0.54, 0.63\} \\
\beta_{04} &= \{0.95, 0.87, 1.00, 0.59, 0.67, 0.68\} \\
\beta_{05} &= \{0.91, 0.65, 1.00, 0.59, 0.65, 0.65\} \\
\beta_{06} &= \{0.69, 0.69, 1.00, 0.87, 0.33, 0.87\} \\
\beta_{07} &= \{0.49, 0.87, 1.00, 0.43, 0.51, 0.63\} \\
\beta_{08} &= \{0.91, 0.83, 0.87, 1.00, 0.56, 0.51\} \\
\beta_{09} &= \{0.67, 0.69, 0.45, 1.00, 0.42, 0.95\} \\
\beta_{010} &= \{0.77, 1.00, 0.63, 1.00, 0.77, 1.00\} \\
\beta_{011} &= \{0.77, 0.57, 0.63, 1.00, 0.69, 1.00\} \\
\beta_{012} &= \{0.71, 0.71, 1.00, 0.51, 0.83, 0.71\}
\end{aligned} \tag{23}$$

Thus, according to formula (22), the gray correlation degree of each group of sample data is calculated, Table 4.

The gray correlation degree calculation results are sorted from large to small.

$$\delta = (\gamma_{010}, \gamma_{04}, \gamma_{08}, \gamma_{011}, \gamma_{012}, \gamma_{06}, \gamma_{05}, \gamma_{02}, \gamma_{03}, \gamma_{09}, \gamma_{01}, \gamma_{07}) \tag{24}$$

It can be seen that the correlation between γ_{010} of the 10th group and the behavioral sequence X_0 of the system

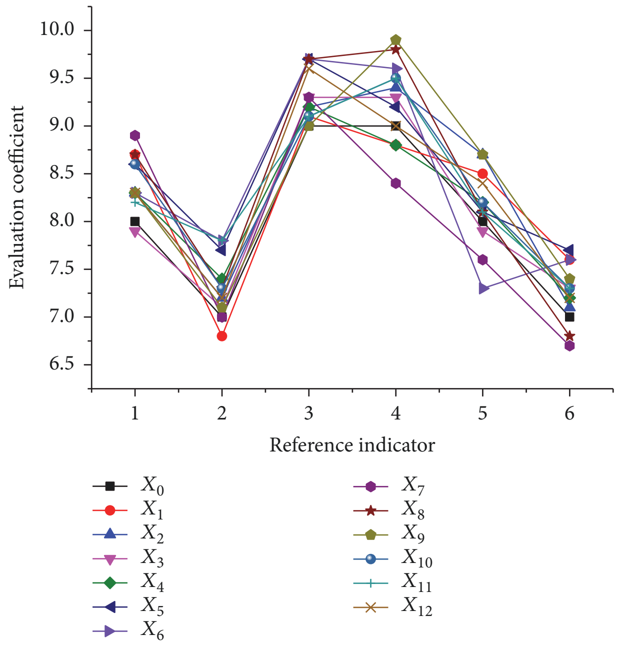

Figure 2: Reliability index data line of the glass sealing characteristic module.

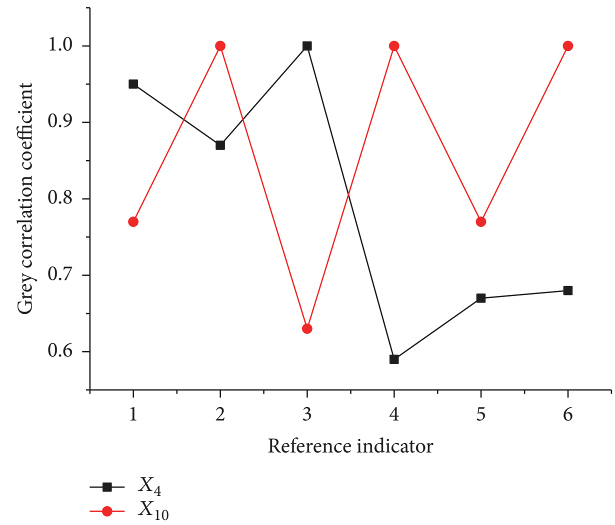

Figure 3: Gray correlation coefficient data lines of test prototype No. 4 and No. 10.

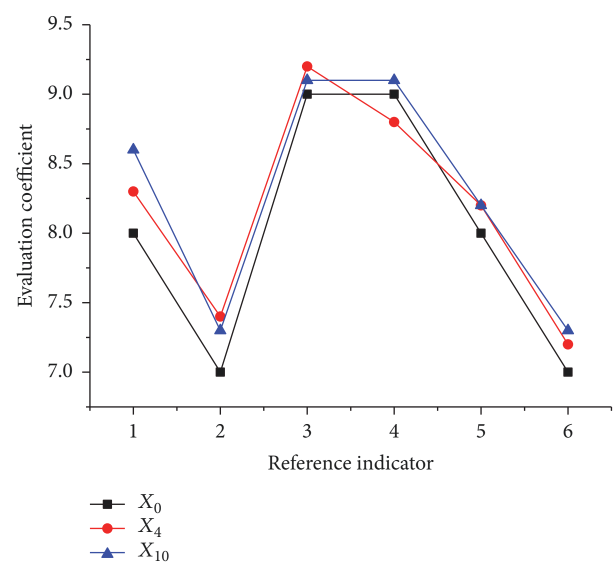

Figure 4: No. 4 and No. 10 test prototype reliability index data line.

characteristic index is the largest. In the reliability test of the mechanical characteristic module, the test results of the 10th test prototype in the 12 groups of test prototypes are most in line with the design standards. To visualize the accuracy of the gray correlation analysis. Draw 12 sets of experimental prototype reliability assessment data line diagram, Figure 2.

In order to visually illustrate the accuracy of gray correlation analysis, draw 12 sets of test prototype reliability index assessment data line diagram, shown in Figure 2.

Figure 2 shows that the six reliability indexes of the mechanical characteristic module, respectively, correspond to six coordinate points. According to the gray correlation analysis model, the closeness of the indexes $X_1, X_2, \ldots, X_{12}$ and X_0 is determined by the closeness of the index values corresponding to the six points with the standard values. The correlation between the corresponding 12 experimental prototype serial lines and the standard data sequence line X_0 in Figure 2 is consistent with the analysis trend of point correlation method. The gray correlation coefficient sequences of the 9th and 4th experimental prototypes with higher gray correlation were compared, Figures 3 and 4.

As can be seen in Figure 3, the gray correlation coefficients of β_{010} and β_{04} are distributed between 0.55 and 1.0. If 0.7 is taken as the reference line, then there are 5 index values of No. 10 test prototype to meet the requirements. No. 4 test prototype has three. If 0.9 is used as a baseline, then 3 indicators are satisfied in prototype 10, while the 4th prototype has only 2 indicators. The analysis shows that the performance of prototype 4 is lower than that of prototype 10.

Figure 4 compares the evaluation data line diagrams and design standard line diagrams of No. 4 prototype and No. 10 experimental prototype. Both X_4 and X_{10} are generally close to the design standard line X_0. It can be found that X_{10} is closer to X_0 than X_4. Therefore, it can be judged that the gray correlation degree of the 10th prototype is higher than that of the 4th prototype. In addition, the 4th evaluation indicator of X_4 did not reach the X_0 design standard value. Therefore, the design scheme of the mechanical characteristics of the No. 4 prototype was eliminated, and No. 10 sample data was selected. It should be pointed out that all reliability indexes that are lower than the design standards are considered to be unqualified prototypes.

It is worth noting that samples with a low degree of gray correlation do not imply a low level of product reliability. Observe the reliability index evaluation data line chart of the five test prototypes of No. 5, No. 9, No. 10, No. 11, and No. 12, as shown in Figure 5.

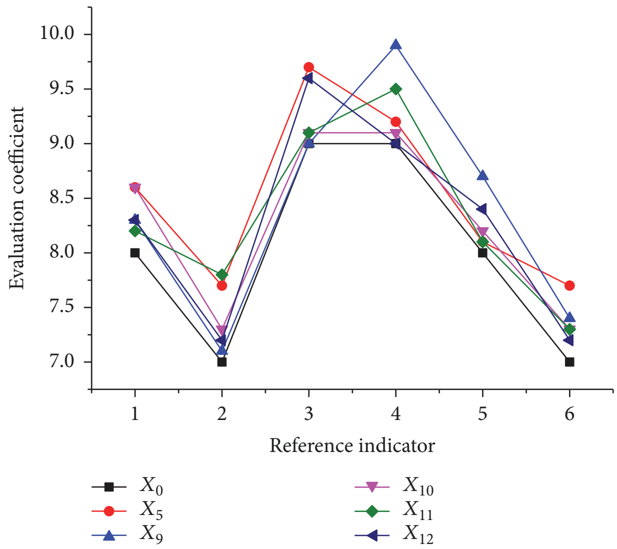

Figure 5: Data line of reliability index of different test samples.

For Figure 5, the evaluation data sequence lines of the five kinds of test prototypes are all higher than the design standard data sequence line X_0. The evaluation index is not lower than the preferred sample X10. However, by carefully comparing the order of the gray correlations, it can be seen that, except for the prototype 10, none of the remaining four prototypes has a high degree of gray correlation with the prototype 10th. However, the specifications of these four prototypes also meet the design requirements. The degree of gray correlation is determined by the proximity of the distance, so it can be determined that the overall proximity of the four prototypes is poor. There are few experimental prototypes that fully comply with the design standards. Therefore, as far as possible to meet the design criteria, we should try to find an experimental prototype with high data correlation with the product reliability design standard. The product mechanical characteristics module adopts the design scheme of No. 10 test sample.

4.2. Gray Relational Analysis of Glass Substrate Characteristic Modules. Analyze the evaluation result of the reliability index of the glass substrate characteristic module. The sequence of glass characteristic behavior indicators of 12 sets of samples was obtained as follows:

$$X_1 = \{8.3, 7.2, 6.9, 7.4\}$$
$$X_2 = \{8.3, 6.8, 7.2, 7.8\}$$
$$X_3 = \{7.7, 7.1, 7.7, 7.6\}$$
$$X_4 = \{7.9, 7.1, 7.3, 7.2\}$$
$$X_5 = \{8.7, 7.1, 7.4, 7.2\}$$
$$X_6 = \{8.1, 7.4, 7.6, 7.7\}$$
$$X_7 = \{8.2, 7.1, 7.1, 7.3\}$$
$$X_8 = \{8.0, 7.2, 7.6, 7.8\}$$

Table 5: Glass substrate characteristics module gray correlation.

sequence	gray relational degree
γ_{01}	0.42
γ_{02}	0.33
γ_{03}	0.365
γ_{04}	0.35
γ_{05}	0.4175
γ_{06}	0.3925
γ_{07}	0.485
γ_{08}	0.3875
γ_{09}	0.3975
γ_{010}	0.415
γ_{011}	0.4825
γ_{012}	0.3825

$$X_9 = \{8.2, 7.4, 7.7, 7.4\}$$
$$X_{10} = \{8.5, 7.4, 7.0, 7.4\}$$
$$X_{11} = \{8.5, 7.8, 7.2, 7.7\}$$
$$X_{12} = \{7.7, 7.4, 7.9, 7.5\} \quad (25)$$

The calculation method is the same as the 3.1 glass airtight property module. The results of the gray correlation obtained are shown in Table 5.

$$\delta = (\gamma_{07}, \gamma_{011}, \gamma_{01}, \gamma_{05}, \gamma_{010}, \gamma_{09}, \gamma_{06}, \gamma_{08}, \gamma_{012}, \gamma_{03}, \gamma_{04}, \gamma_{02}) \quad (26)$$

To sum up, the gray relational degree γ_{07} of the seventh group has the highest correlation with X_0 as the standard sample sequence. In the glass substrate performance module reliability test, the test results of No. 7 test sample in the 12 groups of test prototypes are the most in line with the design standards. According to the results of gray relational degree, like the glass airtightness module, we need to compare the gray relational degree in the glass substrate module. The largest two test samples in the correlation degree series are compared and analyzed. Draw glass substrate characteristic module evaluation index coefficient data chart, as shown in Figure 6.

From Figure 6, we can see that, compared with No. 11 sample No. 7, X7 is closer to the standard sample X0. From this, it can be confirmed that the characteristics of No. 7 prototype in the glass substrate characteristic module are more in line with design requirements.

4.3. Glass Support Selection. The design and placement of the two tempered glass supports are the key to toughening the whole vacuum glass. The excessive contact area between the support and the tempered glass will increase the thermal conductivity and affect the thermal insulation performance of the glass. Therefore, it is necessary to reduce the total number of supports and the volume of individual supports. However, if the contact area of the support is too small, a concentrated load will be formed under the influence of atmospheric pressure. As a result, the tensile stress of the

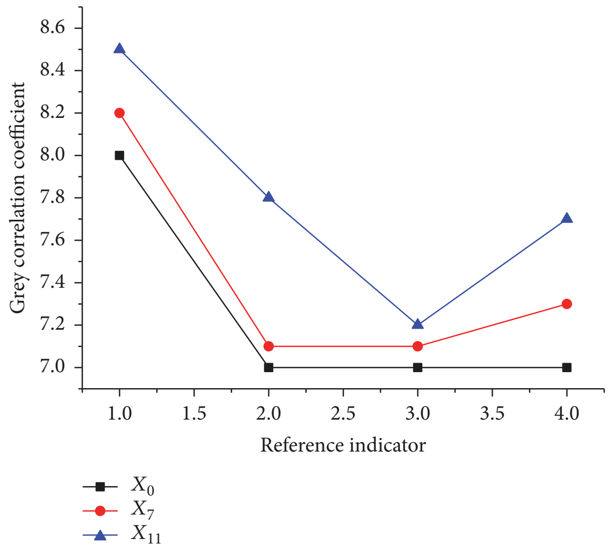

Figure 6: No. 7 and No. 11 test samples reliability index data chart.

tempered glass panel above the support is increased, and the glass surface is easily damaged, which affects the service life. It can be seen that the arrangement of tempered vacuum glass supports will directly affect the overall deformation and stress distribution of the glass. The choice of support module is particularly important.

The choice of the support location is different from the analysis method used by the first two modules. Because the analysis of the previous two modules is based on the analysis of each component as a whole. The reliability index is a reflection of the different reflections of each parameter. Using the gray correlation analysis method is conducive to analyzing the optimal components. In contrast, the optimization of key parts is independent of each other. Supports play an extremely important role in the overall service environment of tempered glass and need to be individually designed or customized.

The reliability evaluation indicators and parameters of the support of the existing 12 sets of prototypes are analyzed. In combination with the assessment results of reliability indicators, the 12 groups of behavioral indicators are as follows:

$$X_1 = \{7.3, 8.5, 6.2, 6.7, 8.8\}$$
$$X_2 = \{7.6, 8.7, 6.6, 6.7, 8.7\}$$
$$X_3 = \{6.9, 8.5, 6.6, 6.5, 8.2\}$$
$$X_4 = \{7.2, 8.2, 6.7, 6.4, 7.9\}$$
$$X_5 = \{7.2, 8.3, 6.2, 6.1, 8.9\}$$
$$X_6 = \{7.2, 7.6, 6.8, 6.4, 8.4\}$$
$$X_7 = \{7.2, 8.7, 6.0, 6.9, 8.5\}$$
$$X_8 = \{6.3, 8.4, 6.9, 6.5, 8.3\}$$
$$X_9 = \{7.6, 7.9, 6.3, 6.2, 7.8\}$$

Table 6: Support site optimization module analysis.

support site indicators	the minimum difference	sample number
strength performance	0.10	11
positioning space	0.20	4,11,12
diameter size	0.00	7
material selection	0.10	5
shape style	0.00	11

$$X_{10} = \{7.2, 7.8, 6.2, 6.6, 7.8\}$$
$$X_{11} = \{7.1, 8.2, 6.2, 6.4, 8.0\}$$
$$X_{12} = \{7.3, 8.2, 6.4, 6.5, 7.9\} \tag{27}$$

The 12 sets of support parts of the module reliability evaluation data for difference processing obtained difference data sequence formula.

$$\Delta_i(k) = \left|x_0(k) - x_i(k)\right| \tag{28}$$

$$\Delta_i = \left(\Delta_i(1), \Delta_i(2), \cdots, \Delta_i(k), \cdots, \Delta_i(n)\right) \tag{29}$$

The above-described 12 sets of difference sequences are included in the following difference matrix M:

$$M = \begin{bmatrix} 0.3 & 0.5 & 0.2 & 0.7 & 0.8 \\ 0.6 & 0.7 & 0.6 & 0.7 & 0.7 \\ 0.1 & 0.5 & 0.6 & 0.5 & 0.2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0.3 & 0.2 & 0.4 & 0.5 & 0.1 \end{bmatrix} \tag{30}$$

Each column of the matrix M is composed of the difference between the reliability test values of the 12 groups of key indicators and the design criteria. Obtain 12 groups of the most similar sample data of reliability index parameters and design standards. According to the minimum difference of each column, find the optimal prototype for each parameter index in the preferred module corresponding to the support site, Table 6.

The principle of gray absolute relevance is still followed in the principle of optimization. Based on the preferred results of the tempered vacuum glass support, the strength data provided by the test sample No. 11 can be selected at the strength properties. The distance between the three test prototypes provided by No. 4, No. 11, and No. 12 can be used as the spacing. The size of the support can be sample size 7 data. Material selection can be reasonably selected based on the information provided in sample data No. 5.

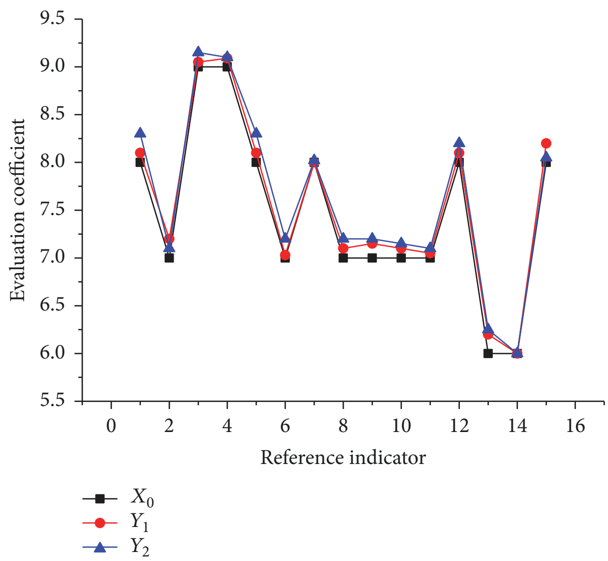

Figure 7: Sample reliability data line of toughened vacuum glass.

5. Reliability Test of Trial Sample of Tempered Vacuum Glass

Combined with the production process of the enterprise, according to the optimized module design scheme, the optimized samples of tempered vacuum glass are produced in small batches. In order to verify the accuracy of the results, a second set of options in the above results was prepared for the sample. The test and evaluation of the reliability index parameters of the two prototypes were carried out. The test results of the trial glass samples are shown in Figure 7. Among them, Y_1 is the evaluation result of the optimal design scheme and Y_2 is the second choice design scheme.

From Figure 7, the tempered vacuum glass meets the design requirements in terms of performance parameters. However, overall the Y_1 prototype can be found to be better than Y_2. Thus, it is basically certain that modular analysis can be applied to the reliability of tempered vacuum glass.

6. Conclusion

(1) The modular multilevel theory was introduced in the reliability design of tempered vacuum glass. Modular analysis is based on product reliability and production design. The reliability data of the tempered vacuum glass is compared with the standard data to judge the standard. The relationship between the test sample evaluation data sequence line and the design standard data sequence line was analyzed. The design requirements for the multiple parameters of tempered vacuum glass are taken into consideration.

(2) Selecting the optimal design module for tempered vacuum glass provides a numerical basis. Realize the reliability analysis of tempered vacuum glass. By using the evaluation results, two sets of trial design schemes were designed. The correctness of the evaluation results was verified through the test evaluation of the trial prototype and comprehensive consideration of its effects.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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