

Article

Experimental Study on the Photothermal Properties of Thermochromic Glass

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Abstract: Reducing energy consumption in buildings is critical to reducing CO₂ emissions and mitigating global warming. Studies have shown that heating and cooling loads account for more than 40% of building energy consumption, and thermochromic glass (TCG) with dynamically adjustable solar transmittance is an excellent way to reduce this load. Although a large number of studies have tested the spectral parameters of TCG in totally transparent and totally turbid states, the impact of dynamic changes in optical properties on the simulation accuracy of building energy consumption has been neglected. In this study, a method is proposed for a hydrogel-type TCG to dynamically test its spectral parameters based on spectrophotometry. The method uses a spectrophotometer and a PID heater to achieve the dynamic optical parameter testing of TCGs at different temperatures. In this paper, the transmission and reflection spectra of the two TCGs at 20~25 °C, 30~35 °C, 40 °C, 45 °C, 50 °C, and 55 °C were obtained, and the regression segmentation functions of visible transmittance and solar transmittance were established. The R² of the function model is 0.99. In addition, the test results show that the thermochromic glass selected in this paper can selectively transmit different wavelengths of light, and its transmission mainly occurs in the visible and near-infrared wavelengths from 320 to 1420 nm, while the transmission rate of other wavelengths is very low. As the temperature increases, the visible, solar, and ultraviolet transmittances decrease at a similar rate. In addition, the higher the temperature acting on the thermochromic (TC) layer, the greater its haze.



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Keywords: thermochromic glass; properties test; spectrophotometer

1. Introduction

1.1. Development Overview of Thermochromic Glazing (TCG)

Conventional insulating and Low-E glass windows used in energy-efficient buildings cannot adjust their radiation transmittance with temperature. In contrast, thermochromic (TC) materials can autonomously regulate solar radiation, reducing transmittance in summer and increasing it in winter, making them ideal for intelligent shading applications. Thermochromic glazing (TCG) has gained attention for its temperature-dependent optical switching, triggered by changes in solar radiation or ambient temperature, without the need for electricity or automated systems [1]. Thermochromism refers to reversible changes in a material's optical properties due to temperature-induced microstructural alterations, affecting transmitted solar radiation. By integrating TC materials like vanadium dioxide (VO₂) into glazing, passive smart windows can be created to control solar gain, daylight, and views [2–4]. TCG, developed from a thermochromic hydrogel, is cost-effective, easy to

produce, and highly temperature-sensitive, transitioning from transparent to frosted states without energy consumption [5].

Thermochromic hydrogels, widely used in tissue engineering, drug delivery, and sensors, have recently gained attention in smart windows for their ability to change transparency. These windows scatter light and reduce transparency with temperature changes, allowing solar light to pass through at room temperature and block it at higher temperatures, without requiring extra energy. Ideal thermochromic smart windows should feature high luminous transmittance, strong solar energy modulation, and a suitable color-change temperature—requirements that hydrogel-based windows easily meet.

1.2. Characteristics of Hydrogel-Based Thermochromic Glazing

Thermochromic hydrogels, such as poly(N-isopropylacrylamide) (PNIPAm), hydroxypropyl cellulose (HPC), polyampholyte hydrogel (PAH), N-vinylcaprolactam (PNVCL), and ethylene glycol-modified pillar arene (EGP5), are promising materials for smart windows. These hydrogels modulate transmittance through reversible hydrophilic/hydrophobic phase transitions around the lower critical solution temperature (LCST). Above the LCST, hydrogen bonds break, polymer chains expand, and hydrophobic interactions dominate. Below the LCST, intermolecular hydrogen bonds form, enabling water–polymer interactions (Figure 1). The polymers initially form a uniform, transparent phase due to intermolecular forces. As the temperature increases, molecular thermal motion intensifies. At a critical temperature, phase separation occurs, producing fine particles that strongly scatter incident light, resulting in the material turning opaque white. By changing the concentration and particle size of TC materials, or adding cosolvents or cross-linkers, their transmittance and diffuse reflectance in transparent and translucent states can be adjusted to meet architectural needs [6–8].

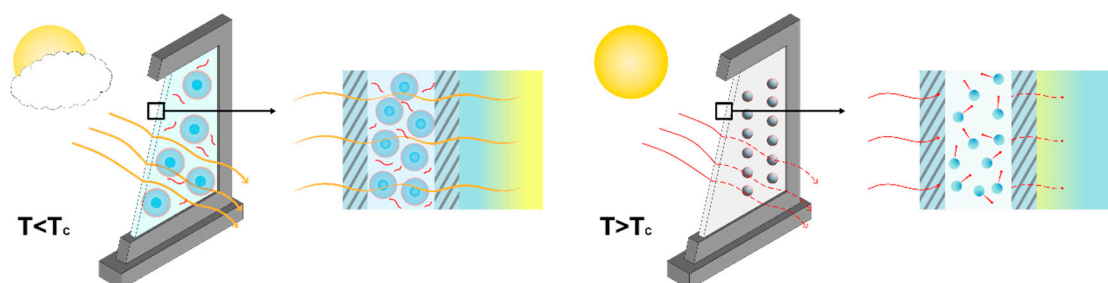


Figure 1. Schematic diagram of the internal structure changes of TC glass in two states.

Studies [9–17] have demonstrated that TC glass exhibits hysteresis during sunlight regulation, characterized by a mismatch between the glass’s color change and temperature variation. When the glass temperature increases, its color changes accordingly; however, upon cooling to the initial temperature, the glass does not fully revert to its original color, displaying a delayed response.

The thermochromic material studied in this paper is a PNIPAm hydrogel, which exhibits two key characteristics: (1) unlike electrochromic glass, it shows hysteresis, and (2) as the temperature rises, most transmitted light becomes scattered (Figure 2). When the temperature exceeds the LCST, the thermochromic film dims, providing shading and heat insulation, and transparency returns as the temperature drops.

TCGs can be divided into two types based on their transmission behavior. The first type, made from vanadium dioxide or chalcogenide, adjusts absorbance during phase transitions. The second type uses nanopolymers, gels, or liquid crystals as the TC layer, which reflects or scatters light when the temperature increases due to phase separation (Figure 3). The first type is called thermochromic (TC) glass in the literature [18], and the

second type is called thermotropic (TT) glass. The key difference between thermochromic (TC) and thermotropic (TT) materials lies in their interaction with solar radiation. TC materials adjust solar transmittance and absorption, maintaining the directionality of transmitted solar radiation, with transparency and color changing as the temperature rises. TT materials, on the other hand, scatter and reflect light as the temperature increases, diffusing and redirecting solar radiation [18,19]. (Although the term TT appears in the literature, this article will still refer to the two types of glass as TC glass).

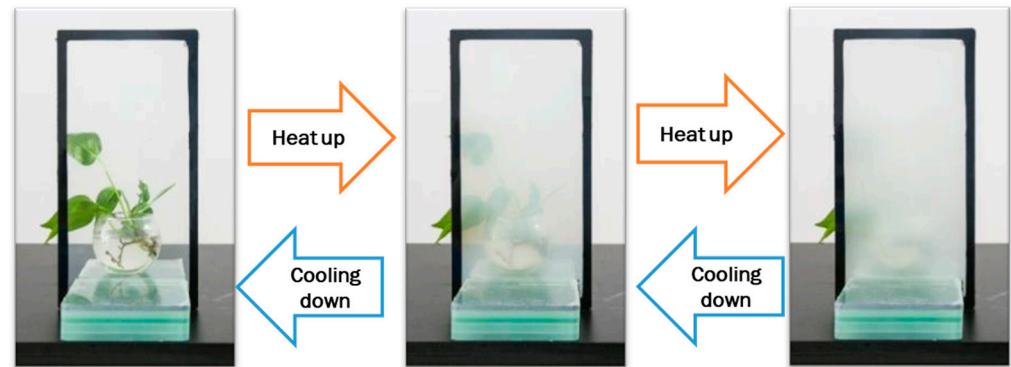


Figure 2. Process of thermochromic glass atomization.

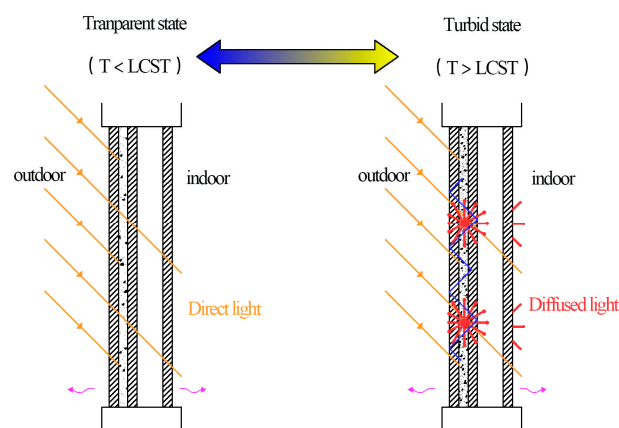


Figure 3. Cross-sectional views of a thermochromic window, air cavity, and rear glass cover. Possible light paths through the window are marked.

Previous studies on hydrogel TC glass have primarily focused on material modification, specifically adjusting its LCST and minimizing hysteresis width. However, there is a lack of spectral measurements of TC glass at varying temperatures. Accurate values of LCST, hysteresis width, and optical performance parameters during the transition state are critical for building energy consumption simulations and architectural design decisions. This study aims to measure the spectral data of TC glass during thermal transitions under controlled laboratory conditions, providing essential data for simulations and architectural applications.

Unlike ordinary glass with static optical properties, the optical parameters of TCGs are dynamic, complicating laboratory testing. Currently, no standardized testing method exists, and key parameters such as visible light transmittance and solar heat gain coefficient for TCGs are lacking. However, accurately modeling the macroscale effects—such as temperature-induced variations in optical properties—is essential for building energy consumption simulations, as these changes influence the interrelated physical domains of a building.

The testing of TCGs faces several challenges: first, controlling the heating and cooling processes is difficult, making it challenging to obtain intermediate state parameters between

the transparent and fully atomized states. Second, since the phase-change material used is a gel rather than thin glass, the measurements must be taken for the entire system. Third, the limited performance of the spectrophotometer makes it difficult to quantify TCG's light scattering ability, which requires more attention. To address this, a wavelength selection method was used to measure the spectral transmittance of TCG at specific wavelengths.

In summary, this study focuses on energy consumption simulation needs and aims to address gaps in existing testing methods by investigating the optical properties and testing protocols of TCGs at different temperatures.

2. Methodology

2.1. Workflow

Part I: Investigate domestic and international testing standards related to TCG, understand the scope of each standard, refer to the specification for the use of the instrument and the calculation procedures, combine with the characteristics of hydrogel TCG, select appropriate experimental equipment, design an experimental testing system, and conduct tests on the selected glass samples.

Part II: Adopt the spectrophotometric method to process the obtained spectral data to derive the glass samples' τ_v , τ_e , ρ_v , ρ_e , $\tau_{v,dir-dif}$ parameters and calculate α_e , Sc , H parameters.

Part III: This part of the work is based on the first round of experimental data and adds missing experimental conditions, analyzes the variation of glass's τ_v , τ_e , determines the relationship between the spectral transmittance of glass and temperature, and establishes a model between the two.

2.2. Test Method for Optical Properties of TCG

2.2.1. Thermochromic Glass Testing Standards

The standard for measuring optical properties of TCG has been summarized in Table 1.

Table 1. The standard for measuring the optical properties of TCG.

Standard	Test/Calculation Parameters	Test Instruments/Calculation Tools	Scope
ISO9050-2003 [20]	$\tau_v, \tau_e, \tau_{uv}$ ρ_v, ρ_e, α_e τ_{df}, F_{sd}, R_a	Spectrophotometer	(a) Conventional and solar control glazing units (b) All transparent materials except for those with significant transmittance in the ambient temperature radiation range (5 μm to 50 μm)
ISO15099 [21]	U, g, τ_v	A procedure for calculating	(a) Single- and double-glazed windows with or without solar control coatings and plastic films (b) Glazing systems with any gas fill (c) Metallic or non-metallic spacers (d) Frames of various materials and designs (e) Windows at any tilt angle (f) Shading devices (g) Projecting window products

Table 1. Cont.

Standard	Test/Calculation Parameters	Test Instruments/Calculation Tools	Scope
ISO10292 [22]	U	A procedure for calculating	(a) Conduction gains in summer (b) Condensation on glazing surfaces (c) Seasonal heat loss through glazing in determining overall energy use in buildings (d) Contribution of absorbed heat in determining the solar factor
ISO10293 [23]	U	Heat flow meter	(a) Multiple glazing with flat and parallel surfaces in the central area and excluding thermal bridge effects from spacers or frames
NFRC300 [24]	τ_v, τ_e $\tau_{v,dir-dif}, \tau_{v,dir-dir},$ ρ_v, ρ_e, α_e	Double-beam ratio-recording spectrophotometer equipped with a multiple-port comparison-type integrating sphere	(a) Clear or slightly hazy single-layer materials (glass and plastics) (b) Coated substrates (glass and plastic) with chemical- or vacuum-deposited coatings (c) Laminated glazing with clear or slightly hazy interlayers (d) Uniformly diffusing materials (fritted glass, etched glass, and diffusing films)
ASTM D1003 [25]	$\tau_{v,dir-dif}, \tau_{v,dir-dir}$ H	Haze meter and spectrophotometer	(a) Evaluation of specific light transmission and wide-angle light scattering properties for transparent materials (b) Materials with a haze value less than 30%
ASTM E903-12 [26]	τ_e, ρ_e, α_e	Spectrophotometer	(a) Materials with both specular and diffuse optical properties (b) Applicable to optical coatings, with special consideration for the texture of the material under test (c) Homogeneous materials
GB/2680-2021 [27]	$\tau_v, \tau_e, \rho_v, \rho_e$ g, g_{IR}, Sc, LSG	Spectrophotometer	(a) Transparent materials such as single glazing and multi-layer glazing
GB/T 5137.2-2020 [28]	τ_v, ρ_v	Target light source, collimating telescope, and spectrophotometer	(a) Automotive safety glass (b) Glass products made from a combination of other materials

Table 1. Cont.

Standard	Test/Calculation Parameters	Test Instruments/Calculation Tools	Scope
GB/T 2410-2008 [29]	T_t, H	Haze meter and spectrophotometer	(a) Transmittance and haze of transparent plastics in the form of plates, sheets, and films.
JG/T 356-2012 [30]	$\tau_v, \tau_{v,dir-dif}, \tau_{v,dir-dir}, \tau_{v,dif-h}, \tau_e, \tau_{e,dif-h}, \rho_e, \rho_{e,dif-h}$	Radiometer Double-beam spectrophotometer	(a) Architectural shading devices, other than fluorescent materials and directional reflective shading devices, parallel to the plane of the glass window
DBJ50/T-367-2020 [31]	Initial thermochromic temperature and complete thermochromic temperature	Haze meter	(a) Thermochromic glass (b) Thermochromic insulating glass
JC/T2670-2022 [32]	$\tau_v, \tau_e, \rho_v, \rho_e, H, Sc$	Haze meter and spectrophotometer	(a) Thermochromic glass with a change in transmission state

Solar radiation, covering the spectrum from 300 to 3000 nm, comprises ultraviolet (UV), visible (VIS), and near-infrared (NIR) light. The visible spectrum ranges from 380 to 780 nm, with UV and NIR wavelengths below and above this range, respectively. When solar radiation interacts with glazing materials, it is partially transmitted, reflected, and absorbed. The proportions of these interactions are determined by the optical properties of the glazing, the wavelength of the radiation, and the angle of incidence. These optical characteristics also influence the angular dependence of transmitted solar radiation, affecting the relative intensities of direct, diffuse, and ground-reflected components. Diffuse light plays a significant role in room illumination, whereas high-energy UV radiation can degrade glazing materials, damage interior furnishings, and pose risks to human skin. Therefore, understanding these optical properties is essential for selecting glazing systems suitable for energy-efficient buildings [33–38]. To evaluate the optical performance of TC glazing systems, a spectrophotometer was employed to measure solar transmission and reflection. Key parameters, including UV transmittance, visible transmittance and reflectance, solar transmittance and reflectance, and solar absorption, were calculated using standard Equations (1)–(5) [20,27].

$$\text{UV transmittance } \tau_{uv} = \frac{\int_{300}^{380} D_{\lambda} \tau(\lambda) V(\lambda) d\lambda}{\int_{300}^{380} D_{\lambda} V(\lambda) d\lambda} \approx \frac{\sum_{300}^{380} D_{\lambda} \tau(\lambda) V(\lambda) \Delta\lambda}{\sum_{300}^{380} D_{\lambda} V(\lambda) \Delta\lambda} \quad (1)$$

$$\text{Visible light transmittance } \tau_v = \frac{\int_{380}^{780} D_{\lambda} \tau(\lambda) V(\lambda) d\lambda}{\int_{380}^{780} D_{\lambda} V(\lambda) d\lambda} \approx \frac{\sum_{380}^{780} D_{\lambda} \tau(\lambda) V(\lambda) \Delta\lambda}{\sum_{380}^{780} D_{\lambda} V(\lambda) \Delta\lambda} \quad (2)$$

$$\text{Visible light reflectance } \rho_v = \frac{\int_{380}^{780} D_{\lambda} \rho_v(\lambda) V(\lambda) d\lambda}{\int_{380}^{780} D_{\lambda} V(\lambda) d\lambda} \approx \frac{\sum_{380}^{780} D_{\lambda} \rho_v(\lambda) V(\lambda) \Delta\lambda}{\sum_{380}^{780} D_{\lambda} V(\lambda) \Delta\lambda} \quad (3)$$

$$\text{Solar transmittance } \tau_e = \frac{\int_{300}^{2500} S_{\lambda} \tau(\lambda) d\lambda}{\int_{300}^{2500} S_{\lambda} d\lambda} \approx \frac{\sum_{350}^{1800} S_{\lambda} \tau(\lambda) \Delta\lambda}{\sum_{350}^{1800} S_{\lambda} \Delta\lambda} \quad (4)$$

$$\text{Solar reflectance } \rho_e = \frac{\int_{300}^{2500} S_\lambda \rho_s(\lambda) d\lambda}{\int_{300}^{500} S_\lambda d\lambda} \approx \frac{\sum_{350}^{1800} S_\lambda \rho_s(\lambda) \Delta\lambda}{\sum_{350}^{1800} S_\lambda \Delta\lambda} \quad (5)$$

where D_λ is the relative spectral distribution of illuminant D65, $V(\lambda)$, which is the spectral luminous efficiency for photopic vision defining the standard observer for photometry, S_λ is the relative spectral distribution of solar radiation, and $\Delta\lambda$ is the wavelength interval. In addition, solar absorption is calculated using the written Equation (6).

$$\text{Solar absorption } \alpha_e = 1 - \tau_e - \rho_e \quad (6)$$

Haze is the ratio of the scattered light flux through the sample deviating from the direction of incident light to the transmitted light flux, that is:

$$\text{Haze } H = \frac{\tau_{v,dir-dif}}{\tau_v} \quad (7)$$

$\tau_{v,dir-dif}$ is the transmittance of scattered light of the sample, and τ_v is the visible light transmittance of the sample.

2.2.2. Thermochromic Glass Experimental Testing System

Optical measurements of TCG samples were carried out using a customized optical bench that combines a spectrophotometer and a temperature-controlled heater to enable the testing of small samples of TCG during temperature changes. The experimental setup for the campaign consists of the following components (Figure 4):

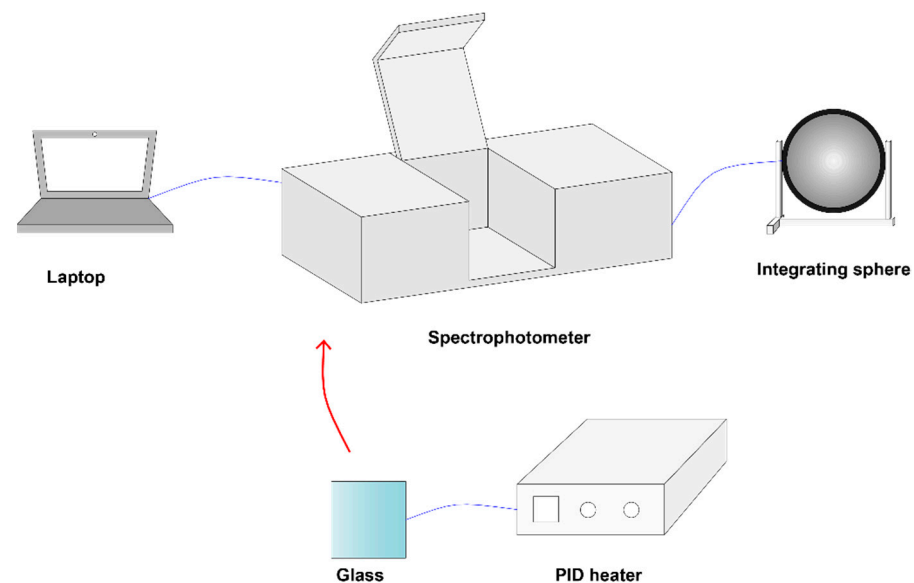


Figure 4. TC glass optical parameter test system.

Spectrophotometer

In order to minimize errors during the testing process, a double-beam spectrophotometer with an integrating sphere was used for this test (Figure 5).

A two-beam spectrophotometer is a frequently used piece of equipment for testing the optical performance of building glass. One beam of light passes through the test sample, and the other beam passes through the reference standard material. Compared with the spectrophotometer with one beam, this method can overcome the adverse factors of unstable light sources and the change of test samples with time. A 300 Watt xenon arc-lamp light source was used, whose radiant power covers the entire visible spectrum and 94% of the solar spectrum, as defined in the relevant standard. The collimated beam can

be modulated through a sequence of lenses and diaphragms, and its size can be adjusted according to the measurement requirements and the geometric complexity of the sample. The light beam diameter was set equal to 60 mm, according to the incident radiation requirements and the characteristics of the thermochromic glass. It is especially suitable for testing TCG.

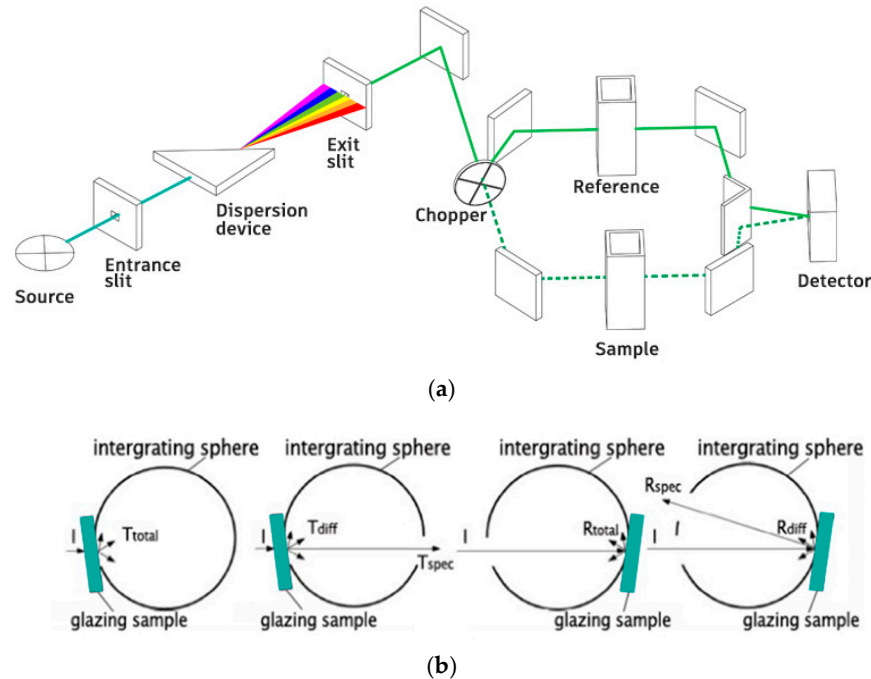


Figure 5. Experimental set-up for measuring transmittance and reflectance: (a) schematic diagram of the double-beam optical path; (b) use of the integrating sphere/spectrometer to qualify transmitted and reflected components.

The spectrophotometer is precalibrated, and the automatically switched iodine tungsten lamp and gas lamp are used as the light source to form a standard D65 light source after passing through the grating. The measurement wavelength range can reach 190–3300 nm, including ultraviolet, visible, near-infrared, and other solar spectral bands. At the same time, it can be equipped with a large-diameter integrating ball, which can obtain high accuracy.

The spectrophotometer is connected to an integrating sphere with an inner diameter of 150 mm and a PTFE coating suitable for diffuse and complex glazing units. The sphere is constituted by an aluminum shell whose internal surface is coated with Spectralon®, which is a highly diffusing material whose reflectivity is greater than 95% over the whole solar spectrum. The sphere is equipped with several ports so that transmittance and reflectance measurements may be performed by means of the auxiliary port method, as required for single beam spectrophotometers. The port diameter of the samples can be varied according to the characteristics of the samples. A 200 mm port was used for this test. The signal (radiant power) collected inside the sphere is transmitted to the detection system via optic fibers.

Integrating Sphere

In the optical performance measurement, errors caused by the following reasons easily occur (Figure 6). However, a standard detector can only receive the direct transmission or specular reflection direction signal. It cannot collect the test scattering signal. Therefore, a detector with an integrating sphere must be selected in this experiment.

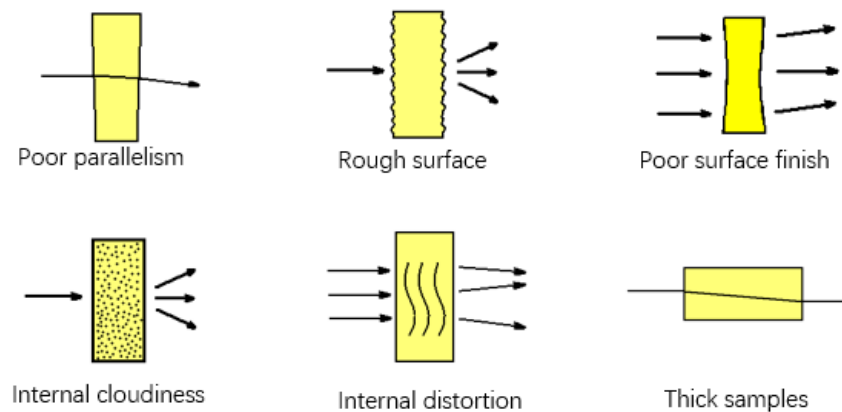


Figure 6. Causes of errors in optical experiments.

PID Heater

The performance parameters of thermochromic glass vary with the temperature acting on its TC layer. To accurately test the performance of TC glass at various temperatures, a stable temperature control system is essential. In this paper, a PID (Proportional–Integral–Derivative control) temperature control system is used. PID control is a widely used in process control in classical control theory and it calculates the precise adjustment of physical quantities (such as temperature, pressure, speed, etc.) in control systems. In temperature control applications, the PID controller receives real-time measurements from temperature sensors and compares them with a set target temperature (setpoint or given value) to produce a control output signal to drive heating or cooling equipment (e.g., heaters, fans, refrigeration compressors, etc.) so that the actual temperature is as close as possible to the setpoint and stabilizes it.

A Test Sample of TCG

This test adopts the sample of 100 mm × 100 mm TCG produced by a Chinese enterprise, with the thickness specification and model of 6 mm + 2 mm + 6 mm, which means that the thickness of the intermediate thermochromic TC layer is 2 mm, and two 6 mm thick clear glasses form the laminated TCG. The TC layer of glass is a film composed of temperature-sensitive color-changing material, film-forming monomer, thickener, dispersant, crosslinking agent, oxidant, reducing agent, etc. The TC materials are mainly PEO-PPO-PEO [20]. The critical temperature of the TC layer is also different according to the proportion of materials. The LCST for samples used in this test are 20 °C and 30 °C, respectively.

2.2.3. Test Procedure

To test the performance of TCG, we must heat the glass and observe its photothermal performance at different temperatures. To ensure the stability of the sample temperature during the test, an electric heating film with a small hole in the middle was used that does not affect the transmission and reflection of the light beam as the heater. The electric heating film is the same size as the glass and is close to the side of the TCG perpendicular to the incident light beam. At the same time, a thermocouple is pasted on both sides of the TCG perpendicular to the incident light beam. The average temperature measured by the two thermocouples is used as the test temperature of the TC glass according to the difference between the test temperature and the set temperature; PID is used to control the heating power of the electric heating film so as to control the sample temperature. After many calibrations, the temperature control error is ± 1 °C. Considering the LCST value of the TCG samples, the hysteresis effect of TCG, the process of heating and cooling during

the experiment, and the accuracy of the PID temperature control system, the experiment was divided into eight groups of temperatures, 20 °C, 25 °C, 30 °C, 35 °C, 40 °C, 45 °C, 50 °C, and 55 °C. During the testing process, the temperature setting of the heater was kept constant, and the TCG specimens were placed in the spectrophotometer for transmission spectra, reflection spectra, etc., so as to obtain the dynamic optical performance parameters at different temperatures.

The optical properties of the two samples of TCG at 20 °C, 25 °C, 30 °C, 35 °C, 40 °C, 45 °C, 50 °C, and 55 °C were tested respectively according to the test scheme described in Section 2.2 and the experimental equipment described in Section 2.2.2. In addition, the transmittance test is for direct light unless otherwise specified.

3. Results

For convenience, the TC glass with a transition temperature of 20 °C and the TC glass with a transition temperature of 30 °C are named TCG 1 and TCG 2, respectively.

3.1. Optical Properties of TCG 1

Figure 7 shows the spectral transmittance of TCG 1 at an ambient temperature of 25 °C. It shows that the thermochromic glass selectively transmits light of different wavelengths. The transmittance of visible light and part of near-infrared light with a wavelength of 320~1420 nm is relatively high; the light transmittance with a wavelength of 1500~1880 nm is low, no more than 10%; and light with a wavelength of 1880~2500 nm can hardly pass through. The visible light passing through TCG 1 is mainly scattered light, and the direct light only accounts for a small part. After calculation, the total transmittance of visible light is 73.6%, while the scattered transmittance is 67.8%, and the haze is 92.1%. Therefore, the visible light penetrates through the TCG in a scattering way, sacrificing the transparency of the window but avoiding the glare of the window and protecting the privacy of the room. It can be applied to positions requiring sun shading and heat protection.

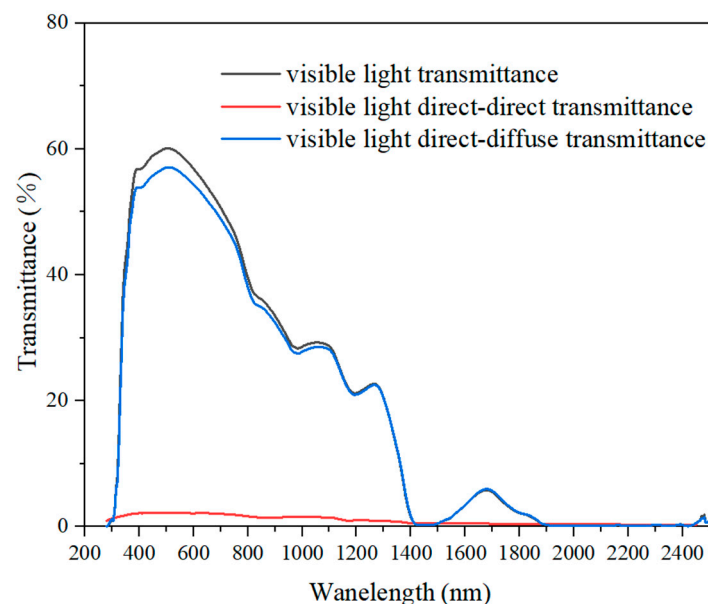


Figure 7. Spectral transmittance of TCG 1 at 25 °C.

Figure 8 shows the spectral transmittance of TCG 1 at different temperatures. It can be seen that the light-selective transmission of thermally induced thermochromic glass to different wavelengths shows a consistent trend at various temperatures. The spectral transmittance of this glass decreases gradually with the increase in ambient temperature.

When the temperature exceeds 35 °C, the spectral transmittance is relatively stable, and the change in transmittance with temperature is not obvious. At this time, it reaches the limit of the sample atomization state.

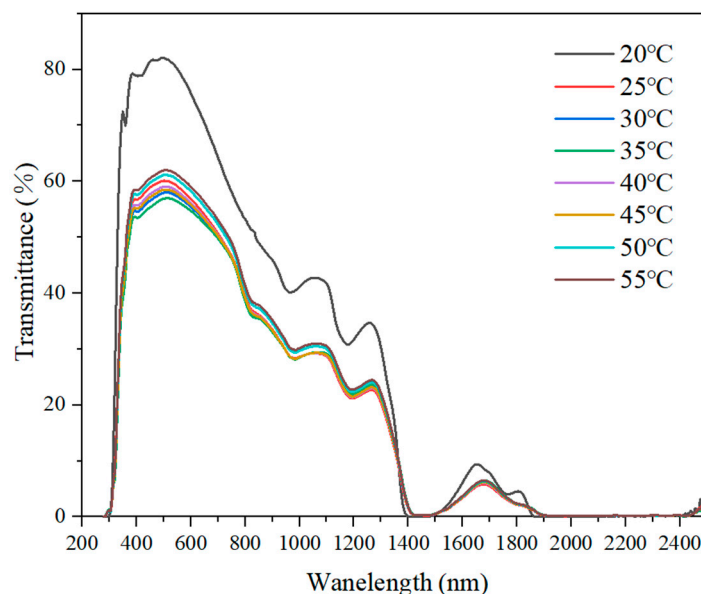


Figure 8. Spectral transmittance of TCG 1 at different temperatures.

3.2. Optical Properties of TCG 2

Figure 9 shows the spectral transmittance of TCG 2 at an ambient temperature of 25 °C. It can be seen that this glass selectively transmits light of different wavelengths, which is consistent with TCG 1. When the wavelength of light is more significant than 1420 nm, the transmittance of light decreases sharply. The difference is that at this time, the visible light passing through the TC glass is mainly direct light, and the scattered light accounts for only a tiny part. After calculation, the total transmittance of visible light is 83.0%, while the direct scattering transmittance of visible light is only 2.1%, and the haze is 2.0%. At this time, TCG 2 is in a transparent state, which does not affect the ability of indoor transmission to the outside world, which is similar to normal glass.

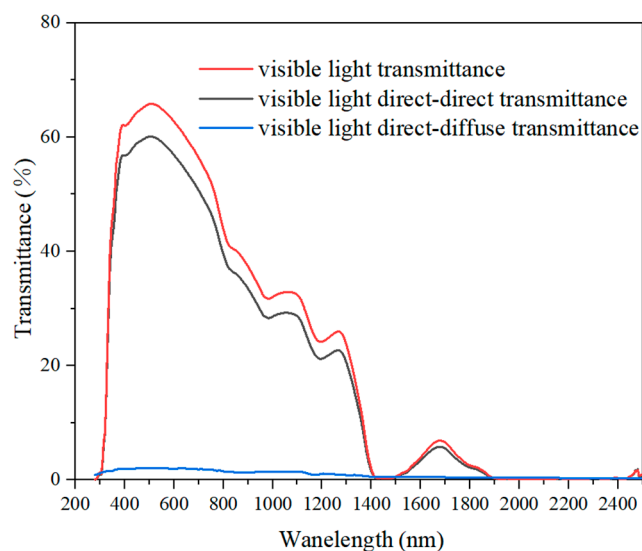


Figure 9. Spectral transmittance of TCG 2 at 25 °C.

Figure 10 shows the spectral transmittance of TCG 2 at different temperatures. It can be seen that when the ambient temperature is 20 °C and 25 °C, the spectral transmittance tends to coincide. It can be seen that when the temperature is lower than 25 °C, the spectral transmittance of TCG 2 does not change. However, when the ambient temperature is greater than 30 °C, the transmittance of this glass gradually decreases with the increase in ambient temperature.

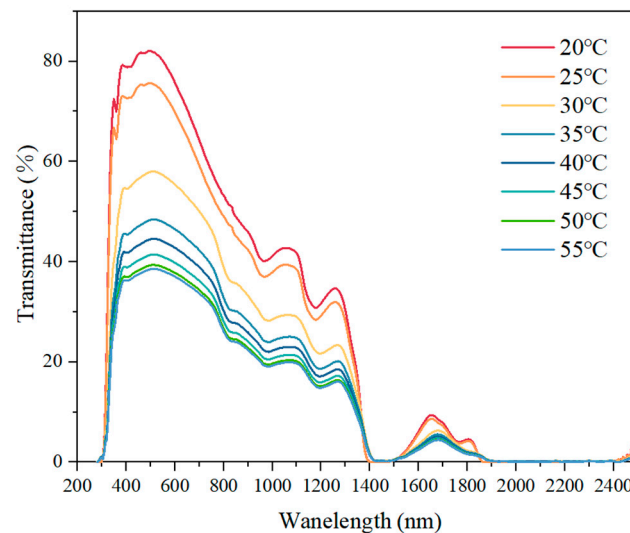


Figure 10. Spectral transmittance of TCG 2 at different temperatures.

3.3. Summary of Optical Performance Test Results of TCG Samples

The optical properties of TC glass at different temperatures are shown in the following Tables. It can be seen from Tables 2 and 3 that with the increase in temperature, the visible light transmittance, sunlight transmittance, and ultraviolet transmittance of the two samples decrease, but they do not change linearly. Similar to the arctangent function, the transmittance change rate of the samples is the fastest at the critical temperature, and the farther away from the critical temperature, the less noticeable the transmittance change rate. Thermochromic glass adopts ordinary glass, and the surface reflectance does not change with temperature. With the increase in temperature, the solar absorption ratio of both samples increases. The more heat absorbed by the thermochromic layer, the more proportion of scattered light will be emitted so that the haze gradually increases and the shading coefficient gradually decreases.

Table 2. Optical properties of TCG 1 at different temperatures.

Temperature	τ_v (%)	$\tau_{v,dir-dif}$ (%)	ρ_v (%)	τ_e (%)	ρ_e (%)	α_e (%)	τ_{uv} (%)	H (%)	Sc
20 °C	78.9	64.4	7.49	53.2	6.19	40.5	67.1	81.60	0.76
25 °C	7.36	6.78	9.18	5.19	7.19	87.6	5.50	92.10	0.39
30 °C	7.35	7.00	11.7	5.18	8.69	86.1	5.49	95.30	0.39
35 °C	6.37	6.11	14.0	4.4	10.09	86.1	4.82	95.90	0.38
40 °C	5.89	5.71	15.7	3.99	11.14	85.5	4.47	97.10	0.37
45 °C	5.84	5.67	16.1	3.98	11.7	84.8	4.44	97.90	0.37
50 °C	5.81	5.68	16.2	3.98	11.8	84.2	4.42	97.10	0.37
55 °C	5.80	5.73	17.0	3.98	11.8	84.2	4.41	98.80	0.37

Table 3. Optical properties of TCG 2 at different temperatures.

Temperature	τ_v (%)	$\tau_{v,dir-dif}$ (%)	ρ_v (%)	τ_e (%)	ρ_e (%)	α_e (%)	τ_{uv} (%)	H (%)	Sc
20 °C	81.5	7.82	8.69	56.5	6.9	36.6	70.5	9.6	0.79
25 °C	79.8	8.13	8.7	54.36	6.87	38.8	69.2	10.2	0.77
30 °C	70.2	12.92	8.71	52.46	6.59	40.9	65.1	18.4	0.76
35 °C	6.93	5.84	8.74	14.48	6.38	79.1	10.0	84.3	0.39
40 °C	6.58	5.63	11.96	4.65	9.07	86.3	4.9	85.6	0.37
45 °C	5.83	5.35	15.07	4.01	10.88	85.1	4.4	91.7	0.37
50 °C	5.62	5.20	18.04	3.83	12.67	83.5	4.2	92.6	0.37
55 °C	5.62	5.18	19.55	3.83	13.46	82.7	4.0	93.9	0.36

The test results demonstrate that the optical parameters of TCG are not fixed values. However, the existing Chinese energy-saving design standard only restricts the summer shading performance of the glass, which requires SC or SHGC to be less than a fixed value and is implemented as a mandatory provision. This regulation limits the promotion of TCG. Take TCG with LCST = 30 °C as an example, at noon on a summer day when the glass temperature reaches 40 °C, TCG in its opaque state may meet the SC requirement. However, in the evening, when the temperature drops to 25 °C and TCG becomes transparent, the SC may exceed the standard's limit. If this regulation is strictly followed, architects cannot choose TCG in the design. In fact, the dynamic characteristics of TCG determine that it is an ideal energy-saving building material. Its equivalent SC value should be calculated comprehensively rather than excluding it from engineering applications because its SC exceeds the standard value in a completely transparent state.

3.4. Spectral Transmittance as a Function of Temperature

From the above conclusion, it can be observed that the spectral transmittance of TCG 1 experiences a significant decrease within the temperature range of 20 °C to 25 °C, while the spectral transmittance of TCG 2 undergoes a substantial decline between 30 °C and 25 °C. This suggests that the hysteresis temperature for the tested TCG samples is approximately 5 °C. To clarify the spectral variation characteristics of TCG within this interval, we conducted an additional round of testing. TCG 1's spectral transmittance was repeatedly measured at temperatures of 20 °C, 21 °C, 22 °C, 23 °C, 24 °C, and 25 °C; similarly, TCG 2's spectral transmittance was retested at temperatures of 30 °C, 31 °C, 32 °C, 33 °C, 34 °C, and 35 °C. We repeated the test five times for each temperature condition and recorded the transmission spectrum data.

From Figures 11–14, the changes in TCG's visible light transmittance and solar light transmittance over time can be fitted into a piecewise function; in the two states of completely transparent state and completely turbid state, the transmittance of TCG is basically stable as a constant; the hysteresis temperature of the tested TCG sample is 5 °C, and during the 5 °C heating process, the transmittance of the glass decreases linearly with the increase in temperature.

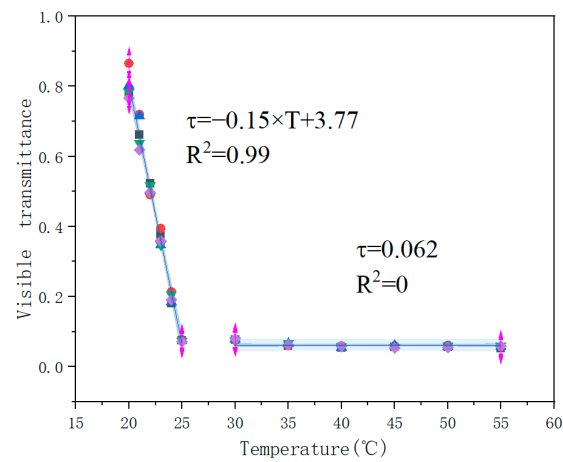


Figure 11. Regression function between visible light transmittance and temperature for TCG 1.

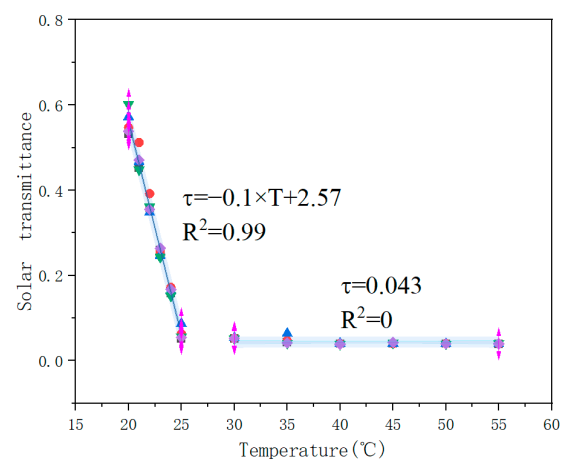


Figure 12. Regression function between solar transmittance and temperature for TCG 1.

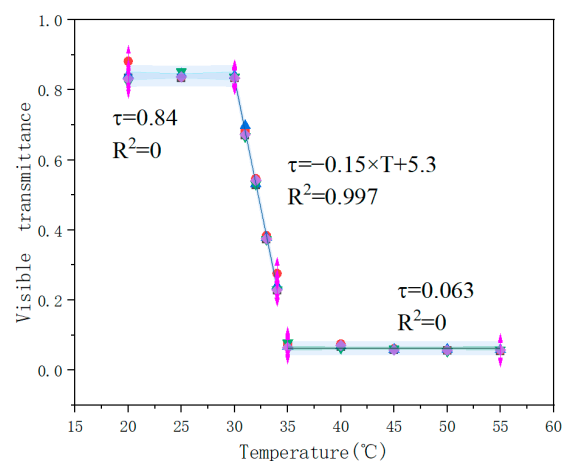


Figure 13. Regression function between visible light transmittance and temperature for TCG 2.

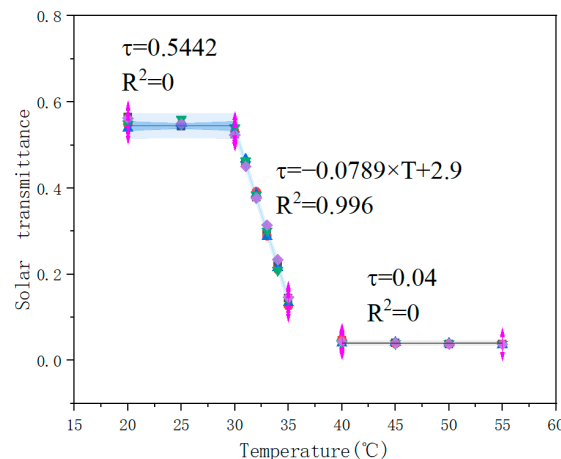


Figure 14. Regression function between solar transmittance and temperature for TCG 2.

4. Discussion

A method is proposed for a hydrogel-type TCG to dynamically test its spectral parameters based on spectrophotometry. This study demonstrates that TCG regulates visible light, near-infrared light, and ultraviolet light. When the temperature of TCG exceeds its LCST, its spectral transmittance decreases, and transmitted light primarily exists as scattered light. This characteristic affects the indoor light environment, particularly in terms of glare, which will be a focus of future research.

The transmittance–temperature relationship of TCG can be approximated as a piecewise function. In energy consumption simulations, this relationship can either be fully integrated or simplified by using parameters from the two extreme states—completely transparent and completely turbid—as in previous studies. Further investigation is needed to evaluate the impact of these two approaches on simulation accuracy. Because the optical parameters of TCG vary with temperature, the weather parameters can be used to count the cumulative hours at different temperatures in a year and the average shading coefficient can be used for design.

The measured hysteresis width of the TCG sample is approximately 5 °C. Future research will explore the role of this hysteresis width in energy consumption simulation accuracy and evaluate how its narrowing or widening could influence building energy efficiency.

Due to experimental limitations, this study utilized 10 × 10 cm samples. However, in practical applications, full-size glass is used, where optical performance is influenced by various factors such as indoor and outdoor solar radiation, air temperature, air conditioning setpoints, and the density of occupants and equipment. Since PID heaters cannot fully replicate these complex heat sources, future research will involve testing TCG in full-scale rooms.

5. Conclusions

This study presents a novel method for dynamically testing the spectral parameters of TCG under varying temperatures, using a double-beam spectrophotometer with an integrating sphere, together with a stable PID temperature control system. Some crucial results were shown as follows:

- (1) The thermochromic glass demonstrates selective light transmission, primarily in the visible (320–1420 nm) and some near-infrared wavelengths, while exhibiting low transmittance in other spectral bands. Its transmittance is high in the transparent state and significantly reduced in the translucent state.

- (2) As the temperature increases, the visible light transmittance, solar light transmittance, and UV transmittance of TCG decrease and the haze gradually increases. This characteristic allows TCG used in building doors, windows, and transparent curtain walls to achieve the purpose of shading and energy efficiency.
- (3) The transmission and reflection spectra of two types of thermochromic glass (TCG) were obtained at temperatures ranging from 20 °C to 25 °C, 30 °C to 35 °C, 40 °C to 45 °C, and 50 °C to 55 °C. A piecewise function model was established for the visible light transmittance and solar light transmittance as a function of temperature, with an R^2 value of 0.99. This function provides a foundational and effective tool for parameter input in building energy consumption simulations and for the selection of TCG during the design phase.

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Nomenclatures

TC	Thermochromic
TCG	thermochromic glass
LCST	lower critical solution temperature
PID	Proportional–Integral–Derivative control
τ_v	Visible light transmittance
τ_{uv}	UV-transmittance
$\tau_{v,dir-dif}$	Visible light direct–diffuse transmittance
$\tau_{v,dir-dir}$	Visible light direct–direct transmittance
$\tau_{v,dif-h}$	Diffuse–hemispherical light transmittance
τ_e	Solar transmittance
$\tau_{e,dif-h}$	Solar direct–hemispherical transmittance
ρ_v	Visible light reflectance
ρ_e	Solar reflectance
$\rho_{e,dif-h}$	Solar direct–hemispherical transmittance
α_e	Sunlight absorption ratio
Sc	Shading coefficient
H	Haze
R_a	General color rendering index
g	Solar energy transmittance
U	Thermal transmittance

Sc	Shading coefficient
g_{IR}	Total solar infrared heat transmittance
LSG	Visible light to total solar energy transmittance
T_t	Luminous transmittance
τ_{df}	CIE damage factor
F_{sd}	Skin damage factor

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