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Journal of Non-Crystalline Solids 261 (2000) 72–78

JOURNAL OF  
NON-CRYSTALLINE SOLIDS

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# Prediction of optical properties of commercial soda–lime-silicate glasses containing iron

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Received 12 May 1999; received in revised form 17 September 1999

## Abstract

We provide a new method to predict the optical absorption of soda–lime-silicate glasses containing low levels ( $\leq 1$  wt%) of iron. We assumed that octahedral and tetrahedral ferric iron as well as octahedral ferrous iron contribute to the optical absorption of the glasses. The absorption coefficients were determined for the respective colorants, and the total transmission spectra were calculated in the wavelength range from 200 to 2100 nm. It has been shown that the calculated spectra agree well with the experimental ones in the entire range of wavelength. We have further calculated such optical properties as visible light transmittance, total solar energy transmittance, and total solar ultraviolet transmittance. It has been demonstrated that these optical properties are satisfactorily reproduced by the calculations. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 78.20.B; 78.66.J; 42.25.B

## 1. Introduction

Recently, so-called ‘solar control glass’, which is usually characterized by a light green tint, has attracted considerable interest in terms of energy savings and protection from ultraviolet (UV) rays [1–3]. Compared to traditional tinted glasses, i.e., gray and bronze glasses, this new type of tinted glass blocks more of the sun’s heat energy and harmful UV rays though it allows more daylight to pass through. Thus, solar control glass is suitable especially for automotive windows and windshields [4–6], showing excellent interior heat-load

reduction performance; it reduces interior heat build-up, protects interior fabrics from the damaging effect of UV rays, and improves passenger comfort by reducing solar radiation.

In order to enhance such insulating effects on tinted glasses, careful choices of UV and/or heat absorbing ingredients and their redox states must be made during the melting stage. One of the most important materials that need to be controlled is iron [4], which absorbs both UV rays and solar heat in the near-infrared region. For this purpose,  $\sim 1$  wt% of total iron is usually introduced into the soda–lime-silicate glasses. For the ultimate in solar control performance, one hence requires precise knowledge of the optical absorption due to iron.

It has generally been accepted that in silicate glasses iron occurs as ferrous ( $\text{Fe}^{2+}$ ) and ferric ( $\text{Fe}^{3+}$ ) states, which give rise to ligand field bands around 1050 and 400 nm, respectively [7,8]. Fur-

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thermore, both ferrous and ferric ions absorb UV light below 350 nm due to the charge transfer process [7,8]. Most of ferrous iron is believed to exist in octahedral coordination as a network modifier [9–11]. On the other hand, ferric iron may exist in fourfold tetrahedral,  $\text{Fe}^{3+}(4)$ , and/or sixfold octahedral,  $\text{Fe}^{3+}(6)$ , coordinations [10–16]. Previous Mössbauer analyses have demonstrated that the ratio  $\text{Fe}^{3+}(6)/\sum \text{Fe}^{3+}$  strongly depends on redox conditions and the total amount of iron in glasses [10–14]. Furthermore, optical absorption measurements have suggested that both octahedral and tetrahedral ferric ions contribute to the ligand field bands around 400 nm and the charge-transfer UV absorption [12]. This indicates that in order to explain the optical properties of commercial soda–lime–silicate glasses, one has to take into account the absorption bands due to octahedral as well as tetrahedral ferric iron.

As mentioned above, Mössbauer measurements allow one to determine the ratio  $\text{Fe}^{3+}(6)/\sum \text{Fe}^{3+}$  in glasses. It should be noted, however, that this technique can only be applied to glasses containing a large amount ( $\lesssim 10$  wt%) of iron. In glasses such as those in solar control glass containing low levels ( $\lesssim 1$  wt%) of iron, one cannot determine the relative proportion of octahedral to tetrahedral ferric iron experimentally. From these reasons, there has been no satisfactory way to predict the optical absorption of commercial tinted glasses from the experimental data available. We must hence rely mostly on trial and error to improve the optical properties of the existing tinted glasses.

In this paper, we, therefore, provide a new method to predict the optical properties of commercial soda–lime–silicate glasses containing iron from experimental total iron (as  $\text{Fe}_2\text{O}_3$ ) and total ferrous and ferric iron contents. It is expected that this method not only gives a new insight into color generation in solar control glass but also provides a physical basis of the absorption spectra of soda–lime–silicate glasses containing iron. On the basis of the method proposed, we calculate the absorption spectra and some optical properties (visible light transmittance [VLT], total solar energy transmittance [TSET], and total solar ultraviolet transmittance [TSUV]) of the glasses. We then compare the calculated results with the ob-

served ones and discuss the applicability of the method.

## 2. Experimental procedures

The base glass composition chosen for the present work (in wt%) is  $71.9\text{SiO}_2 \cdot 1.4\text{Al}_2\text{O}_3 \cdot 3.8\text{Mg}_2\text{O} \cdot 9.1\text{CaO} \cdot 13.8\text{Na}_2\text{O}$ . This is a typical composition widely used for float soda–lime–silicate glass in the glass industry. The glasses were melted in 90Pt–10Rh (wt%) crucibles in air at  $1450^\circ\text{C}$  for 4 h. After melting, the melts were cast onto a stainless-steel mould and then annealed at  $650^\circ\text{C}$  for 30 min to prevent internal stress.

Iron was added in the form of  $\text{Fe}_2\text{O}_3$  without changing the relative ratio of the above base glass composition; over 20 glass samples were prepared by changing the total iron content from  $\sim 0.2$  to  $\sim 1.0$  wt%. Iron redox was controlled by adding appropriate amounts of reducing (pure carbon) and oxidizing ( $\text{Na}_2\text{SO}_4$ ) agents. As a result, a trace amount of  $\text{SO}_3$  ( $\sim 0.2$  wt%) remained in the glasses depending on the carbon/ $\text{Na}_2\text{SO}_4$  ratio. Wet chemical analyses were routinely carried out to determine the ferrous iron content. Total iron contents were measured by X-ray fluorescence spectrometry, which enables us to derive the total iron content as  $\text{Fe}_2\text{O}_3$ . Table 1 shows the iron content of some glass samples used in this work. Ground and polished samples with thickness of 5 mm were used for transmission measurements with a spectrophotometer in the range from 200 to 2100 nm. The random errors in the transmittance were estimated by measuring the transmission spectra of the same sample several times. We also measured the reflectivity,  $R$ , of several samples at an angle of incidence of  $5^\circ$ . We obtained almost the same  $R$  values for all the samples we measured.

On the basis of the transmission spectra, we calculated the following optical properties to characterize solar control performance:

1. Visible light transmittance measured by illuminant A (VLTa), which is the ratio (%) of luminous radiant energy transmitted by an object to that incident upon it for an incandescent tungsten filament lamp in the 380–780 nm wavelengths.

Table 1

Examples of iron contents (wt%) of glasses used in this work

| Sample number                                              | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     |
|------------------------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Total Fe (as Fe <sub>2</sub> O <sub>3</sub> ) <sup>a</sup> | 0.926 | 0.972 | 0.663 | 0.754 | 0.834 | 0.884 | 0.191 | 0.197 | 0.386 |
| FeO <sup>b</sup>                                           | 0.175 | 0.213 | 0.124 | 0.139 | 0.149 | 0.221 | 0.035 | 0.038 | 0.074 |
| Fe <sub>2</sub> O <sub>3</sub> <sup>c</sup>                | 0.734 | 0.739 | 0.527 | 0.602 | 0.670 | 0.642 | 0.152 | 0.155 | 0.305 |

<sup>a</sup>Total Fe contents were expressed as Fe<sub>2</sub>O<sub>3</sub> contents derived from the X-ray fluorescence spectrometry. The measurements errors are  $\pm 0.002$  wt%.

<sup>b</sup>FeO contents were determined from the wet chemical analyses. The measurements errors are  $\pm 0.003$  wt%.

<sup>c</sup>Fe<sub>2</sub>O<sub>3</sub> contents were determined by subtracting the FeO equivalent from the X-ray fluorescence derived total iron as Fe<sub>2</sub>O<sub>3</sub> contents.

2. TSET, which is the ratio (%) of total solar radiant energy transmitted by an object to that incident upon it in the 300–2000 nm wavelengths.
3. TSUV, which is the ratio (%) of ultraviolet radiation transmitted by an object to that incident upon it in the 295–400 nm wavelengths.

### 3. Method

#### 3.1. Absorption coefficients of octahedral Fe<sup>2+</sup> and tetrahedral Fe<sup>3+</sup>

When there is no mutual interaction between colorants  $i$  embedded in the glass structure, transmittance  $T$  (%) of glass can be expressed as follows:

$$T(\lambda)/100 = (1 - R(\lambda))^2 \exp\left(-\sum_i \alpha_i(\lambda)c_i t\right), \quad (1)$$

where  $R(\lambda)$  is the reflectivity at wavelength  $\lambda$ ,  $\alpha_i$  and  $c_i$  the absorption coefficient and the concentration of  $i$ th colorant ion, respectively, and  $t$  is the thickness of the glass.

For glasses containing only octahedral ferrous and tetrahedral ferric iron as colorizing agents, the transmission spectrum can be described simply as

$$\begin{aligned} T(\lambda)/100 &= (1 - R(\lambda))^2 \exp(-\alpha_{\text{ferrous}(6)}(\lambda) \\ &\quad \times [\text{Fe}^{2+}(6)]t - \alpha_{\text{ferric}(4)}(\lambda) \\ &\quad \times [\text{Fe}^{3+}(4)]t), \end{aligned} \quad (2)$$

where  $[\text{Fe}^{2+}(6)]$  and  $[\text{Fe}^{3+}(4)]$  mean the octahedral ferrous and tetrahedral ferric iron contents, respectively. In such a special case, since the experimental ferrous and ferric iron contents can be used as the values of  $[\text{Fe}^{2+}(6)]$  and  $[\text{Fe}^{3+}(4)]$ , the

absorption coefficients of both two types of iron can be calculated from the absorption data of any two glass samples.

On the basis of this scheme, we first calculated the absorption coefficients of octahedral ferrous and tetrahedral ferric iron by selecting two glass samples with a total iron concentration less than  $\sim 0.47$  wt%. We then repeated the procedure by changing the combination of the two samples in this series of glasses and obtained several sets of  $\alpha_{\text{ferrous}(6)}(\lambda)$  and  $\alpha_{\text{ferric}(4)}(\lambda)$ . For convenience, we used  $\text{wt}\%^{-1} \text{ mm}^{-1}$  instead of  $\text{l mol}^{-1} \text{ cm}^{-1}$  as a unit of the absorption coefficient since the former unit is expected to scale linearly with the latter unit for glasses containing low levels ( $\lesssim 1$  wt%) of iron. Consequently, we have found that there is no appreciable scatter among the values of  $\alpha_{\text{ferrous}(6)}(\lambda)$  and  $\alpha_{\text{ferric}(4)}(\lambda)$  throughout the wavelength range of interest, suggesting that Eq. (2) indeed holds for all the glasses containing less than  $\sim 0.47$  wt% of total iron. Fig. 1 shows the values of  $\alpha_{\text{ferrous}(6)}(\lambda)$  and

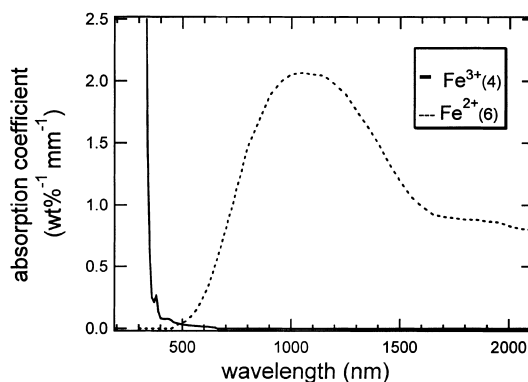


Fig. 1. The wavelength dependence of absorption coefficients of tetrahedral Fe<sup>3+</sup> (Fe<sup>3+</sup>(4)) and octahedral Fe<sup>2+</sup> (Fe<sup>2+</sup>(6)) obtained for the soda–lime–silicate glasses containing iron.

$\alpha_{\text{ferric}(4)}(\lambda)$ , which were obtained by averaging all the sets of data mentioned above.

However, if we employ two glass samples containing more than  $\sim 0.6$  wt% total iron, the resultant absorption coefficients have been found to depend strongly on the samples used for the calculations. This indicates that such a simple scheme as shown in Eq. (2) cannot be applied to glasses containing more than  $\sim 0.6$  wt% of total iron; that is, the effect of octahedral ferric iron must be considered for a complete understanding of the coloration mechanism due to iron.

From these preliminary calculations, it can be said that as far as the soda–lime–silicate glasses containing less than  $\sim 0.47$  wt% of total iron are concerned, the contribution of octahedral ferric iron, even if present, to the transmission spectra is negligibly small, and Eq. (2) will allow us to obtain the absorption coefficients of  $\text{Fe}^{2+}(6)$  and  $\text{Fe}^{3+}(4)$ .

#### 4. Absorption coefficients of octahedral $\text{Fe}^{3+}$

We next propose a scheme to predict optical absorption data of glasses having both tetrahedral and octahedral ferric iron as well as octahedral ferrous iron as colorants. In such a case, the transmission spectrum can be described as

$$\begin{aligned} T(\lambda)/100 &= (1 - R(\lambda))^2 \exp(-\alpha_{\text{ferrous}(6)}(\lambda) \\ &\quad \times [\text{Fe}^{2+}(6)]t - \alpha_{\text{ferric}(4)}(\lambda) \\ &\quad \times [\text{Fe}^{3+}(4)]t - \alpha_{\text{ferric}(6)}(\lambda) \\ &\quad \times [\text{Fe}^{3+}(6)]t). \end{aligned} \quad (3)$$

In order to calculate the transmission spectrum according to the above equation, we further require the absorption coefficient of octahedral ferric iron  $\alpha_{\text{ferric}(6)}(\lambda)$ . However, the determination of the values of  $\alpha_{\text{ferric}(6)}(\lambda)$  is not as straightforward as in the case of  $\alpha_{\text{ferrous}(6)}(\lambda)$  and  $\alpha_{\text{ferric}(4)}(\lambda)$  because, as mentioned above, we cannot measure the  $\text{Fe}^{3+}(4)$  and  $\text{Fe}^{3+}(6)$  contents experimentally for glasses with less than  $\sim 1$  wt% of total iron.

Thus, in this study we made the following assumptions to estimate the contents of  $\text{Fe}^{3+}(4)$  and  $\text{Fe}^{3+}(6)$  in soda–lime–silicate glasses:

(i) The fraction of octahedral ferric iron,  $R = [\text{Fe}^{3+}(6)]/[\sum \text{Fe}^{3+}]$ , has been found to increase as the amount of ferric iron decreases in glasses containing the same total iron [11,14,16]; in other words, the fraction of  $\text{Fe}^{3+}(6)$  increases as the ratio  $\text{Fe}^{2+}(6)/\sum \text{Fe}$  increases. We hence assumed that for glasses containing the same total iron, the  $R$  value increases linearly with  $\text{Fe}^{2+}(6)/\sum \text{Fe}$ , namely,  $R = k_1[\text{Fe}^{2+}(6)]/[\sum \text{Fe}]$ , where  $k_1$  is a constant depending on the total amount of iron, and, therefore, the content of octahedral ferric iron can be written as

$$[\text{Fe}^{3+}(6)] = k_1 \left[ \sum \text{Fe}^{3+} \right] \left( [\text{Fe}^{2+}(6)] / \left[ \sum \text{Fe} \right] \right). \quad (4)$$

(ii) It has been shown that the relative concentration of  $\text{Fe}^{3+}(6)$  increases with increasing total iron if melt redox conditions are not drastically changed [14]. We, therefore, assumed that the value of  $k_1$  in Eq. (4) increases linearly with total iron  $\sum \text{Fe}$ , namely,  $k_1 = k[\sum \text{Fe}]$ , where  $k$  is a constant.

From the above assumptions,  $[\text{Fe}^{3+}(6)]$  can eventually be written as

$$\begin{aligned} [\text{Fe}^{3+}(6)] &= k \left[ \sum \text{Fe} \right] \left[ \sum \text{Fe}^{3+} \right] \left( [\text{Fe}^{2+}(6)] / \left[ \sum \text{Fe} \right] \right) \\ &= k [\text{Fe}^{2+}(6)] \left[ \sum \text{Fe}^{3+} \right] v. \end{aligned} \quad (5)$$

(iii) Furthermore, it is reasonable to assume that the  $\text{Fe}^{3+}(4)$  content is equal to  $[\sum \text{Fe}^{3+}]$ ; that is

$$[\text{Fe}^{3+}(4)] = \left[ \sum \text{Fe}^{3+} \right], \quad (6)$$

since the amount of  $\text{Fe}^{3+}(6)$  is expected to be very small compared with that of  $\text{Fe}^{3+}(4)$  in the present series of glasses.

Using Eqs. (5) and (6), we then obtain the following form to represent the transmission spectrum of the glasses of interest:

$$T(\lambda)/100 = (1 - R(\lambda))^2 \exp \left( -\alpha_{\text{ferrous}(6)}(\lambda) \times [\text{Fe}^{2+}(6)]t - \alpha_{\text{ferric}(4)}(\lambda) \left[ \sum \text{Fe}^{3+} \right]t - k\alpha_{\text{ferric}(6)}(\lambda) [\text{Fe}^{2+}(6)] \left[ \sum \text{Fe}^{3+} \right]t \right). \quad (7)$$

Consequently, the absorption coefficient of octahedral ferric iron can be written as follows:

$$k\alpha_{\text{ferric}(6)}(\lambda) = \left( -\ln((T(\lambda)/100)/(1 - R(\lambda))^2) - \alpha_{\text{ferrous}(6)}(\lambda) [\text{Fe}^{2+}(6)]t - \alpha_{\text{ferric}(4)}(\lambda) \left[ \sum \text{Fe}^{3+} \right]t \right) / \left( [\text{Fe}^{2+}(6)] \times \left[ \sum \text{Fe}^{3+} \right]t \right). \quad (8)$$

All the terms in the right-hand side of Eq. (8) are experimentally measurable. Thus, we can calculate the value of  $k\alpha_{\text{ferric}(6)}$  at respective wavelengths. Fig. 2 shows the wavelength dependence of  $k\alpha_{\text{ferric}(6)}$  obtained for the glass samples containing more than  $\sim 0.6$  wt% of total iron (for details, see Table 1). The transmittance in the wavelength region shorter than 320 nm was almost zero, and we did not obtain the values of  $k\alpha_{\text{ferric}(6)}$  for such a shorter-wavelength region.

If the above assumptions can be actually applied to the present soda–lime–silicate glasses, we will obtain uniform values of  $k\alpha_{\text{ferric}(6)}$  for all the

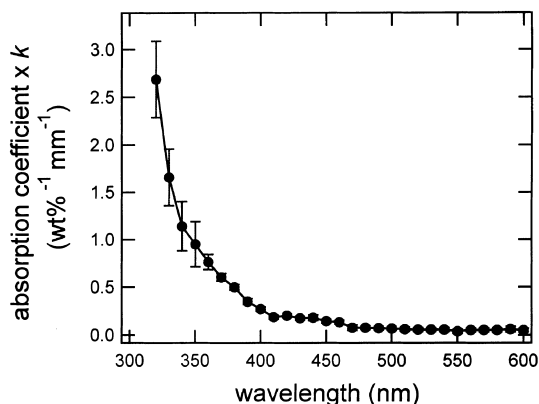


Fig. 2. The wavelength dependence of  $k\alpha_{\text{ferric}(6)}$  obtained for the soda–lime–silicate glasses containing iron. The line is a guide for the eye.

glass samples used for the calculations. Fig. 2 indeed shows that there is no considerable scatter among the calculated values of  $k\alpha_{\text{ferric}(6)}$  in the visible wavelength region. Although one sees a relatively large scatter in the UV region, in a later section we will demonstrate that the values of  $k\alpha_{\text{ferric}(6)}$  obtained in this work are consistent with the UV charge-transfer process, which is believed to be the main absorption mechanism of octahedral ferric iron in the UV region [12]. These results hence suggest that Eqs. (7) and (8) based on assumptions (i)–(iii) will capture some fundamental features of the iron coloration in glass and are expected to be used to predict the optical properties of the present series of soda–lime–silicate glasses.

## 5. Results

Using the values of  $k\alpha_{\text{ferric}(6)}$ ,  $\alpha_{\text{ferric}(4)}$ ,  $\alpha_{\text{ferrous}(6)}$ , we can calculate the transmission spectrum of glass according to Eq. (7). Before going into details derived from Eq. (7), however, we show what happens if one neglects the effect of octahedral ferric iron on the transmission spectrum. Fig. 3(a) compares the transmission spectrum of sample 1 (see Table 1) predicted from Eq. (2) with the corresponding experimental spectrum. Since sample 1 contains 0.926 wt% total iron, it is expected that Eq. (2) will not predict the spectrum satisfactorily because of neglect of the absorption due to octahedral ferric iron. Indeed, the calculated transmission spectrum underestimates the absorption in the wavelength range from  $\sim 350$  to  $\sim 600$  nm, which corresponds to the range of absorption due to octahedral ferric iron given in Fig. 2.

We then calculate the transmission spectrum of the same sample according to Eq. (7); the calculated spectrum is illustrated in Fig. 3(b). In contrast to the results shown in Fig. 3(a), one finds an excellent agreement between the calculated and experimental spectra in the entire wavelength range from  $\sim 300$  to 2100 nm. We further confirmed such a good agreement between the calculated and experimental spectra for all the glass samples listed in Table 1.

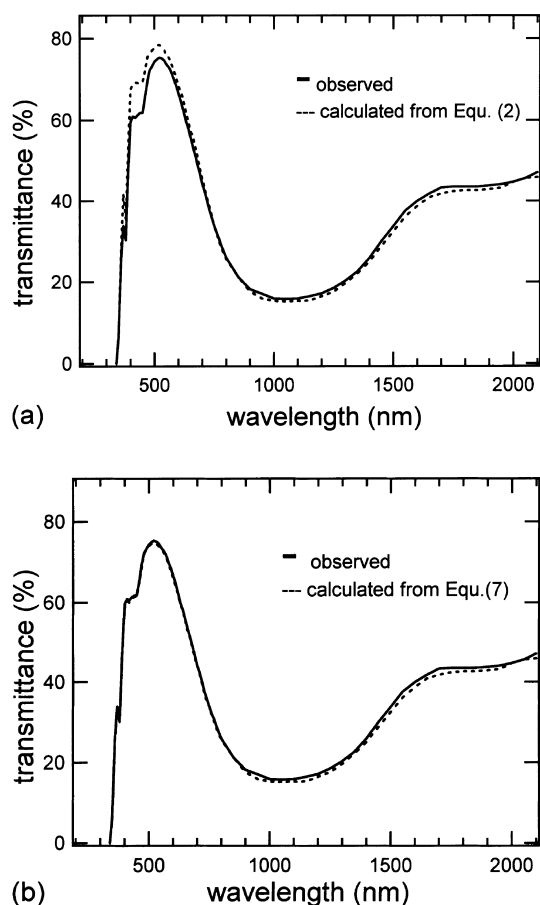


Fig. 3. Transmission spectra of sample 1 calculated from (a) Eq. (2) and (b) Eq. (7). The corresponding observed spectrum is also shown.

Thus, Eq. (7) will serve as quantitative representation of the experimental absorption data for soda–lime–silicate glasses containing iron. It is interesting to calculate their optical properties that

characterize solar control performance of the glasses. On the basis of the transmission spectra derived from Eq. (7), we calculate VLTa, TSET and TSUV of samples 1–9 shown in Table 1. Table 2 compares these calculated solar properties with the observed ones. One sees from Table 2 that there is an excellent correspondence between the calculated and observed VLTa, while the calculated TSET and TSUV agree fairly well with the corresponding observed ones. It should also be worth mentioning that such a good correspondence can be seen not only for the glasses containing  $\sim 0.6$  to  $\sim 1.0$  wt% of total iron (samples 1–6) but also for those containing less than  $\sim 0.4$  wt% of total iron (samples 7–9). It is hence most likely that Eq. (7) holds for all the soda–lime–silicate glasses with a total iron concentration up to  $\sim 1.0$  wt%.

## 6. Discussion

As shown in Fig. 2, octahedral ferric iron contributes to the absorption in the UV region as well as in the visible region. In the UV region, the values of  $k\alpha_{\text{ferric}(6)}$  increases rapidly with decreasing wavelength, which reminds us of a charge-transfer process as in the case of tetrahedral ferric iron. On the other hand, the absorption in the visible region is most likely due to the ligand field bands.

If  $\text{Fe}^{3+}(6)$  contributes to the charge-transfer process in the UV region, the absorption behavior will obey Urbach's rule in this wavelength range, resulting in a linear plot of  $\log k\alpha_{\text{ferric}(6)}$  against wavenumber [12,17]. Fig. 4 indeed shows that Urbach's rule is followed down to  $\sim 400$  nm ( $25000 \text{ cm}^{-1}$ ). This result clearly demonstrates

Table 2

Observed and calculated (in parenthesis) optical properties of the present glass samples<sup>a</sup>

| Sample number | 1              | 2              | 3              | 4              | 5              | 6              | 7              | 8              | 9              |
|---------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| VLTa (%)      | 69.6<br>(69.4) | 66.0<br>(66.4) | 75.2<br>(75.7) | 73.6<br>(73.7) | 72.0<br>(72.2) | 71.0<br>(71.1) | 86.2<br>(86.5) | 86.8<br>(86.4) | 82.1<br>(82.2) |
| TSET (%)      | 42.6<br>(42.3) | 37.8<br>(37.7) | 50.3<br>(51.6) | 47.7<br>(48.5) | 45.6<br>(46.4) | 43.5<br>(43.3) | 73.6<br>(74.2) | 75.9<br>(74.3) | 63.0<br>(64.1) |
| TSUV (%)      | 28.3<br>(27.7) | 27.0<br>(26.0) | 37.5<br>(38.2) | 33.9<br>(34.3) | 30.8<br>(31.2) | 35.3<br>(34.7) | 67.0<br>(66.5) | 66.1<br>(65.7) | 52.6<br>(52.6) |

<sup>a</sup> The measurement errors are  $\pm 0.1\%$  for VLTa and TSET and  $\pm 0.2\%$  for TSUV, respectively.

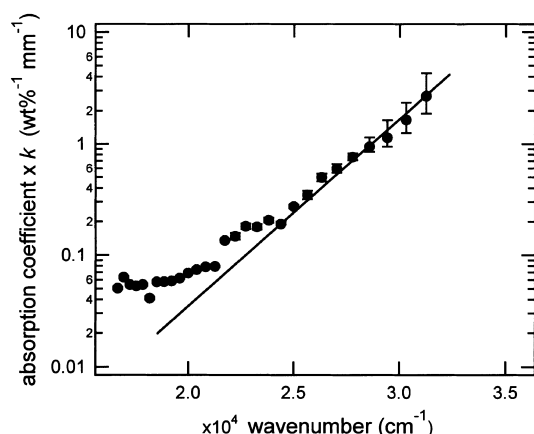


Fig. 4. The wavenumber dependence of  $\log k\alpha_{\text{ferric}(6)}$  (an Urbach plot) for the present glass samples.

that the UV absorption due to  $\text{Fe}^{3+}(6)$  certainly results from the charge-transfer process. That is, although the wavenumber dependence of  $k\alpha_{\text{ferric}(6)}$  was obtained from several assumptions as mentioned above, the present values of  $k\alpha_{\text{ferric}(6)}$  have a sound physical basis and is consistent with the previous investigation on the coloration mechanism of iron in soda–lime–silicate glasses [7,12,17].

## 7. Conclusions

It has been found that for soda–lime–silicate glasses containing less than  $\sim 0.47$  wt% of total iron the contribution of  $\text{Fe}^{3+}(6)$  to the optical absorption is negligible, indicating that the absorption due only to  $\text{Fe}^{2+}(6)$  and  $\text{Fe}^{3+}(4)$  should be taken into account to explain the observed spectra. For glasses containing more than  $\sim 0.6$  wt% of total iron, however, the absorption due to  $\text{Fe}^{3+}(6)$  must be included for the full description of the observed transmission spectra. It has been elucidated that octahedral ferric iron contributes to the absorption in the wavelength region below  $\sim 600$  nm including the UV region.

On the basis of the above findings, we determined the absorption coefficients of these three types of iron ions in soda–lime–silicate glasses. We made several assumptions to estimate the amounts

of tetrahedral and octahedral ferric iron in the glasses and finally reached Eq. (7), which can predict the transmission spectra of the glasses only from the observable data. Although Eq. (7) is based on several empirical assumptions, the correspondence between the calculated and experimental spectra was almost perfect in the entire range of wavelength, and, accordingly, some optical properties (VLTa, TSET, and TSUV) were satisfactorily reproduced. Thus, we conclude that this method can be used to predict the optical properties of the commercial solar control glass and will shed new light on the optical absorption due to iron in soda–lime–silicate glasses.

## Acknowledgements

The authors are grateful to K. Sakaguchi at Nippon Sheet Glass Company Ltd. for helpful discussion and careful reading of the manuscript.

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