

**The relationship between local structure and photo-Fenton catalytic ability of glasses and glass-ceramics prepared from Japanese slag**

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# Title page

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# The relationship between local structure and photo-Fenton catalytic ability of glasses and glass-ceramics prepared from Japanese slag

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## Abstract

Local structure and the photo-Fenton reactivity of iron-containing glasses and glass-ceramics prepared from Japanese domestic waste slag were investigated. The largest rate constant ( $k$ ) of  $(2.8 \pm 0.08) \times 10^{-2} \text{ min}^{-1}$  was recorded for the methylene blue degradation test by using  $\text{H}_2\text{O}_2$  with a heat-treated ‘model slag’. The  $^{57}\text{Fe}$  Mössbauer spectrum was composed of a paramagnetic doublet with isomer shift of  $0.18 \pm 0.01 \text{ mm s}^{-1}$  attributed to

distorted  $\text{Fe}^{\text{III}}\text{O}_4$  tetrahedra. These results indicate that the paramagnetic  $\text{Fe}^{3+}$  provided strong photo-Fenton catalytic ability, and that waste slag can thus be recycled as an effective visible-light activated photocatalyst.

## Article Highlights

- 1- Waste slag was used to prepare glass samples for photocatalytic applications.
- 2- The degradation of methylene blue solution was enhanced by adding hydrogen peroxide.
- 3- Irradiating the samples with sunlight has a positive effect on the catalyst performance.

## Keywords

Domestic waste slag;  $^{57}\text{Fe}$ -Mössbauer spectroscopy; visible-light activated photocatalytic effect; photo-Fenton reaction; methylene blue; Iron oxide

## 1- Introduction

Waste materials are a severe problem worldwide. The Organization for Economic Co-operation and Development (OECD) reported that the annual total amount of municipal waste discarded from the OECD affiliated countries exceeds an estimated 650 million tons (522 kg per capita) [1]. Hence, recycling or reuse of waste material is becoming essential. In Japan and other countries, incineration plants have been established to meet the lack of landfill sites. The by-product of the incineration plants is slag, which is mainly used at present as civil engineering filler materials and as raw materials for the cement industry [2].

On the other hand, organic pollutants in wastewater are a significant problem worldwide. Since its discovery in Japan in 1972 by Fujishima and Honda [3], materials with photocatalytic activity have received great interest and a number of applications. The applications of photocatalytic materials that mineralize and decompose organic pollutants

have drawn a lot of benefits. Photoactivity using  $\text{TiO}_2$  is a good solution for the degradation of organic materials, however, its photoactivity can only be activated under UV light due to the wide band gap of  $\text{TiO}_2$ , 3.2 eV. Various conventional semiconductors have been tested as low bandgap photocatalysts. Among these,  $\text{Fe}_2\text{O}_3$  is low cost, has a narrow band gap of 2.2 eV, is non-toxic, chemically stable and is thus an environmentally friendly material [4].

If the slag discarded from combustion plants, which contains  $\text{Fe}_2\text{O}_3$ , can be used as a photocatalytic material, this will be a low-cost alternative to high-cost materials such as  $\text{TiO}_2$ , and can thus enhance application of this technology whilst increasing the economic return from incineration plants. Some research refers to the possibility of achieving such a goal, for example Kubuki *et al.* [5] reported that  $15\text{Na}_2\text{O}\cdot 15\text{CaO}\cdot 50\text{Fe}_2\text{O}_3\cdot 20\text{SiO}_2$  (weight %) glass showed a visible-light activated photocatalytic effect. The sample after heat treatment at 1000 °C for 100 min caused decomposition of  $10\text{ }\mu\text{mol L}^{-1}$  methylene blue (MB) with a first-order rate constant ( $k$ ) of  $4.78 \times 10^{-4}\text{ min}^{-1}$  [5]. Iron-containing aluminosilicate glass, which has a similar composition to slag,  $15\text{Na}_2\text{O}\cdot 15\text{CaO}\cdot 40\text{Fe}_2\text{O}_3\cdot 11\text{Al}_2\text{O}_3\cdot 19\text{SiO}_2$  (weight %), also showed a photocatalytic effect after heat treatment at 1000 °C for 100 min, having a larger  $k$  of  $9.26 \times 10^{-3}\text{ min}^{-1}$  for MB degradation [6]. It is noted that the visible-light activated photocatalytic effect of iron-containing silicate glass was enhanced by introducing  $\text{Al}_2\text{O}_3$ . Kubuki *et al.* [7, 8] also reported that iron silicate glass prepared by recycling the ash discharged from municipal solid waste combustion plant (MSW ash) was effective in reducing the chemical oxygen demand (COD) of artificial wastewater [7, 8].

Ishikawa *et al.* [9] reported that heat treatment of waste slag recycled glass-ceramics (WSRG) with additional  $\text{Fe}_2\text{O}_3$  content of 10, 30 and 50 mass % decomposed MB aqueous solution with a first-order rate constant ( $k$ ) of  $2.6 \times 10^{-3}$ ,  $2.3 \times 10^{-3}$  and  $2.7 \times 10^{-3}\text{ min}^{-1}$ , respectively, under visible-light irradiation. The absorption area for the fitted  $\alpha\text{-Fe}_2\text{O}_3$  component in  $^{57}\text{Fe}$ -Mössbauer spectra showed an almost identical amount of nanoparticles of 4.3, 4.0 and 4.5 mass % in heat-treated WSRG with  $\text{Fe}_2\text{O}_3$  content of 10, 30 and 50 mass %, respectively. These results are consistent with the conclusion that the visible light-

activated the photocatalytic effect of heat-treated WSRG is closely related to the precipitated amount of  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> nanoparticles [9].

As an Advanced Oxidation Process (AOP), the Fenton reaction and the light-accelerated Fenton reaction, commonly known as the photo-Fenton reaction, appear to be promising for practical industrial applications [10-13]. When Fenton reaction systems are irradiated with UV/Visible light, this can accelerate the rate of degradation of a wide variety of pollutants. This behaviour upon irradiation is due principally to the photochemical reduction from Fe<sup>III</sup> to Fe<sup>II</sup>. Advantages of the photo-Fenton reaction include producing an additional hydroxyl radical, the species responsible for the degradation of organic material, and regeneration of Fe<sup>II</sup> by light with the decomposition of water. As a consequence, the amount of H<sub>2</sub>O<sub>2</sub> needed to convert Fe<sup>III</sup> to Fe<sup>II</sup> is reduced [11]. The significant advantage of the Fenton process is that the reagent components are safe to handle and environmentally friendly. Highly complicated apparatus and pressurized systems are not required for the oxidation process, making it a feasible technology for upscaling directly from laboratory-scale to full-scale [12]. Above all, if sunlight is used, the photo-Fenton treatment is far cheaper than other available AOP's such as ozonization [13].

The photocatalytic activity of oxide semiconductors is commonly considered in terms of the effect of the band gap energy. The wide band gap of TiO<sub>2</sub> (3.2 eV) is one factor hampering improvements towards more efficient devices working under a wide range of solar energies [14]. Photocatalytic tests carried out in photodecomposition of dipropyl sulfide showed good correlation between the band gap energy and the photocatalytic activity for metallophthalocyanine complexes [15]. ZnO as a semiconductor photocatalyst has the same drawback [16, 17]. Mohamed and Barakat [17] synthesized ZnO-SiO<sub>2</sub> nanoparticles by a sol-gel technique. The samples were further modified by nanosized Pt from H<sub>2</sub>PtCl<sub>6</sub> solution through photoassisted deposition (PAD) and impregnation (Img) routes. As a result, the band gap energy has been decreased from 3.40 eV for ZnO-SiO<sub>2</sub> to 3.25, 3.05 eV for Img: Pt-ZnO-SiO<sub>2</sub>, and PAD: Pt-ZnO-SiO<sub>2</sub>, respectively. Phenol degradation efficiency increased from 80 to 85 and 99.9%, with the ZnO/SiO<sub>2</sub>, Img: Pt-ZnO-SiO<sub>2</sub>, and PAD: Pt-ZnO-SiO<sub>2</sub> samples, respectively [17].

In this work, we investigate the relationship between the structure and photocatalytic ability of glass and glass-ceramic samples prepared by melt-quenching and subsequent heat treatment, from recycled waste-slag by means of X-ray diffraction (XRD),  $^{57}\text{Fe}$ -Mössbauer spectroscopy, transmission electron microscopy (TEM) and ultraviolet-visible absorption spectroscopy (UV-VIS).

## 2- Experimental

### 2. 1. Sample preparation:

One kg of waste slag was collected on July 14<sup>th</sup>, 2015 at Tamagawa municipal domestic waste combustion plant (Maruko 2-33-1, Ohta-ward, Tokyo 146-092, Japan). The chemical composition of this slag was previously analysed and reported to be CaO (21.79 mass%); SiO<sub>2</sub> (23.32); Fe<sub>2</sub>O<sub>3</sub> (11.45); Al<sub>2</sub>O<sub>3</sub> (16.68); Na<sub>2</sub>O (6.57) and other minor components (20.19) [9]. A series of glass and glass-ceramic samples with different Fe<sub>2</sub>O<sub>3</sub> concentration, (11 mass %, 14, 30 and 50) were prepared by a melt-quench method using the above described pulverized slag named SF11 Original, with varying levels of addition of Fe<sub>2</sub>O<sub>3</sub>. The mixtures of SF11 Original and Fe<sub>2</sub>O<sub>3</sub> were melted at 1400 °C for 1 h in a platinum crucible. Samples without Fe<sub>2</sub>O<sub>3</sub> additions, and with Fe<sub>2</sub>O<sub>3</sub> additions, to adjust total Fe<sub>2</sub>O<sub>3</sub> content to 30% and 50% were obtained by quenching the base of the crucible in ice-cold water. These samples are named as SF11 Melted, SF30 Melted and SF50 Melted, respectively.

In order to evaluate the effect of impurities, simulated slag glass was prepared from the chemical reagent of the main components excluding the other minor components, named as RSF14 Melted. The prepared samples and their Fe<sub>2</sub>O<sub>3</sub> additions are listed in Table 1. Reagent chemicals used were Na<sub>2</sub>CO<sub>3</sub> (Wako 199-01585), CaCO<sub>3</sub> (Wako 030-00385), Fe<sub>2</sub>O<sub>3</sub> (Wako 096-04825), Al<sub>2</sub>O<sub>3</sub> (Wako 012-01965) and SiO<sub>2</sub> (Kanto Kagaku 37974-00), they were well mixed in an agate mortar before sample preparation. All prepared samples were also separated, and a fraction of each was subjected to heat treatment at 800 °C for 100 min.

## 2. 2. Characterization techniques:

Sample structures before and after heat treatment were characterized by  $^{57}\text{Fe}$  Mössbauer spectroscopy, X-ray diffractometry (XRD), and transmission electron microscopy (TEM).  $^{57}\text{Fe}$  Mössbauer spectra were measured using a constant acceleration spectrometer. A source of 925 MBq  $^{57}\text{Co}(\text{Rh})$  was attached to an MVT-1000 transducer connected to a MDU-1200 drive unit. The drive unit was connected to a DFG-1200 digital function generator, then to an ORTEC 570 amplifier. Transmitted  $\gamma$ -rays through the sample were detected by a photomultiplier tube. The counts were amplified by an ORTEC 142 preamplifier. The applied voltage (2 kV) was obtained by using an ORTEC 556 High voltage power supply, and an ORTEC 570 amplifier. The amplified signals were monitored with a PC via an ORTEC EASY-MSC. Samples with weight = 40 mg were homogeneously dispersed in a circular sample holder with 10 mm diameter; inserted into the spectrometer; and measured until the total counts collected were greater than  $10^6$ . Isomer shifts were given relative to  $\alpha\text{-Fe}$  as a reference. The Mösswinn 3.0i XP software was used to analyze the obtained spectra.

XRD patterns were recorded using a TKYD07-028, Rigaku diffractometer between  $2\theta$  of 10 to 80, with precision and scan rates of 0.02 and 5 degrees / minute, respectively.  $\text{Cu-K}\alpha$  rays ( $\lambda = 0.1541$  nm) were generated with a monochromator under 50 kV and 300 mA. TEM images were obtained using a JEM-3200FS Field Emission Energy Filter Electron Microscope.

For the evaluation of photocatalytic properties, we used 40 mg of pulverized sample and 10 mL of methylene blue aqueous solution ( $\text{MB}_{\text{aq}}$ ) with an initial concentration of  $20\ \mu\text{mol L}^{-1}$ . An additional amount (0.36 ml) of Hydrogen peroxide (9.79 M) (Wako: 081-04215 30% mass/mass) was added to the MB solution. The concentration of  $\text{H}_2\text{O}_2$  in this solution was 0.34 M. UV–Vis spectra of the MB solution before and after the photocatalytic reaction test were obtained from the absorbance of the peak at 665 nm. The light was emitted by a metal-halide lamp with output wavelength region from 420 to 750 nm, an output power of 100 W and an intensity of  $6\ \text{mW cm}^{-2}$ , with the distance between the



sample and the light source maintained at 20 cm, and a UV filter to remove UV light. All samples were also measured in the dark to investigate the effect of adsorption.

For the evaluation of photocatalytic properties using sun light irradiation, the UV light intensity was ca. 5 mW/cm<sup>2</sup> in Hachioji (longitude 139.24, altitude 35.62), and temperature was 27 – 29 °C.

Diffuse reflectance spectra (DRS) were recorded between the wavelength of 190 and 1500 nm using a UV-VIS spectrometer with an integrating sphere. Barium sulfate was used as a reference in the diffuse reflection measurements. Sampling pitch and slit-width were set at 1.0 nm and 20 nm, respectively.

### **3. Results and discussion**

#### **3.1. Structural characterization:**

##### **3.1.1 XRD patterns:**

Fig. 1 shows the XRD patterns for all samples before and after heat treatment at 800°C for 100 minutes. Before heat treatment, samples SF11 Original, SF11 Melted and RSF14 Melted show halo patterns, confirming the amorphous structure of these samples, while samples SF30 Melted and SF50 Melted are not glasses but glass-ceramics. Sample SF30 Melted produces diffraction peaks ascribed to magnetite (Fe<sub>3</sub>O<sub>4</sub>, PDF No. 96-900-9769), while sample SF50 Melted produces higher intensity peaks assigned to magnetite (Fe<sub>3</sub>O<sub>4</sub>, PDF No. 96-900-5840) and hematite (Fe<sub>2</sub>O<sub>3</sub>, PDF No. 96-901-5066). These results indicate that homogenous glass can be obtained with iron oxide contents of < 30%, while samples containing > 30% of iron oxide or more are glass-ceramics where the crystalline phase/s can be detected.

After heat-treatment at 800 °C for 100 min, sample SF11 Original produces broad diffraction peaks attributed to Gehlenite ( Al<sub>2</sub>Ca<sub>2</sub>SiO<sub>7</sub>, PDF No. 96-100-0049) and

magnetite (  $\text{Fe}_3\text{O}_4$ , PDF No.96-151-3305). Sample SF11 Melted shows diffraction peaks with higher intensity due to Esseneite (  $\text{Al}_{1.34}\text{CaO}_{0.97}\text{Fe}_{0.61}\text{O}_6\text{Si}_{1.08}$ , PDF No. 96-900-1042) and alpha-dicalcium silicate (  $\text{Ca}_2\text{SiO}_4$ , PDF No. 96-154-6029). Sample RSF14 Melted shows more clear crystalline peaks attributed to (  $\text{AlSiO}_7$ , PDF No. 96-154-0253) and magnetite (  $\text{Fe}_3\text{O}_4$ , PDF No. 96-900-2330). Interestingly, sample SF30 Melted after heat treatment shows the same peaks of the magnetite phase at almost the same diffraction angle due to magnetite (  $\text{Fe}_3\text{O}_4$ , PDF No. 96-900-7707). For sample SF50 Melted, the detected diffraction peaks were assigned to magnetite (  $\text{Fe}_3\text{O}_4$ , PDF No. 96-101-1033) and hematite (  $\text{Fe}_2\text{O}_3$ , PDF No. 96-901-5066). It was noticed that for sample SF50 Melted, the hematite phase increased in abundance due to oxidation during heat-treatment, while the magnetite phase decreased in abundance. These results are consistent with the obtained Mössbauer spectra.

### 3.1.2 Mössbauer spectra:

For RT Mössbauer spectroscopy, the spectra and parameters of all samples before and after heat-treatment are shown in Fig. 2 and Table 2, respectively. Before heat treatment, sample SF11 Original exhibits two doublets, one related to  $\text{Fe}^{\text{II}} T_d$ , the second is related to  $\text{Fe}^{\text{III}} O_h$ . Sample SF11 Melted shows one doublet related to  $\text{Fe}^{\text{III}} T_d$ . RSF14 Melted has one doublet related to  $\text{Fe}^{\text{III}} T_d$ . Increasing the iron content to 30% and 50% results in three sextets only for sample SF50 Melted, with one assigned as (magnetite + maghemite), the second as magnetite, and the third as hematite. It also shows a doublet attributed to  $\text{Fe}^{\text{III}} T_d$ . The sample SF30 Melted shows only one doublet, attributed to  $\text{Fe}^{\text{III}} O_h$ .

After heat-treatment, all samples except for sample SF50 Melted show doublets with  $\delta = (0.18 \pm 0.01) - (0.38 \pm 0.01 \text{ mm s}^{-1})$ . Only sample SF11 Original has an additional doublet due to  $\text{Fe}^{\text{II}} O_h$  with a small spectral area (and hence abundance) of 9.8%. Sample SF50 Melted produces a doublet related to  $\text{Fe}^{\text{III}} T_d$  and two sextets due to hematite and

maghemite. The increase in the hematite component for sample SF50 Melted from 9.8% before heat treatment to 38.1% after heat treatment matches the XRD measurements.

The best performing samples for the photo-Fenton reaction were samples RSF14 Melted and SF11 Melted. The room temperature Mössbauer spectra for those samples show no magnetic components, so the heat treated samples were measured at 77 K to provide further investigation. The spectra and fitted parameters are shown in Fig. 3 and Table 3, respectively. It can be seen that for samples SF11 Original, SF11 Melted and RSF14 Melted, no magnetic components are detected. Unlike the room temperature spectra, for sample SF30 Melted, one doublet arises from  $\text{Fe}^{\text{III}} T_d$  and three sextets arise from (maghemite + magnetite), hematite, and magnetite, respectively. Sample SF50 Melted produces two sextets (one due to hematite and one to maghemite), and one doublet due to  $\text{Fe}^{\text{III}} T_d$ .

### 3.1.3 TEM Images:

TEM images for the heat-treated samples are shown in Fig. 4. The SF11 Original sample is mostly amorphous (see XRD pattern). Sample SF11 Melted has nanoparticles with a size of ca. 10 nm and crystalline structure can be seen at high magnification. Sample RSF14 Melted shows a crystalline structure and nanoparticle sizes varying from 10 - 70 nm. For sample SF30 Melted, nanoparticles with size varying from 20 - 30 nm were detected, while for sample SF50 Melted no nanostructure can be observed, even with very high magnification. These results confirm the precipitation of iron nanoparticles during melting at 1400 °C and / or quenching; and that the size of the nanoparticles is broadly correlated to the iron content of the sample.

### 3.2. Photocatalytic activity measurements:

Fig. 5 (dotted lines) shows the pseudo-first-order rate constant ( $k$ ) of MB decomposition in the presence of the different samples after heat-treatment. The best-performing samples

were SF30 Melted and SF50 Melted, both with  $k = (3.00 \pm 0.08) \times 10^{-3} \text{ min}^{-1}$ . These samples have the highest iron oxide contents. The samples SF11 Original and SF11 Melted also have the same  $k$ -value of  $(2.30 \pm 0.06) \times 10^{-3} \text{ min}^{-1}$ , this is mostly due to the similarity in structure. The sample RSF14 Melted has the lowest  $k$ -value of  $(1.80 \pm 0.05) \times 10^{-3} \text{ min}^{-1}$ .

To investigate the similarity in structure, diffuse reflectance spectroscopy (DRS) was used to measure the band gap for all samples after heat treatment. The degradation of blank (MB solution without catalyst) and dark samples (MB and catalyst without visible light irradiation) were measured. For these measurements, the pseudo-first-order rate constant ( $k$ ) of MB decomposition was small compared to the irradiated samples, with  $k = (0.70 \pm 0.02)$  and  $(0.20 \pm 0.01) \times 10^{-3} \text{ min}^{-1}$ , respectively. All samples were also measured before heat treatment, providing a maximum  $k$ -value of  $(1.00 \pm 0.03) \times 10^{-3} \text{ min}^{-1}$ .

#### **DRS measurements:**

The bandgap energies of the heat-treated samples were measured using diffuse reflectance spectroscopy. The band gap energy ( $E_g$ ) was estimated using the following equation, a Tauc plot [18]:

$$(h\nu\alpha)^{1/n} = A(h\nu - E_g) \quad (1)$$

where  $h$ ,  $\nu$ ,  $\alpha$ ,  $n$  and  $A$  are Plank's constant, frequency of light, absorption coefficient,  $n$  is a number that characterizes the transition process, in this case ( $n = 0.5$ ) and  $A$  is the proportionality factor. Fig. 6 shows the Tauc plot used to calculate the band gap; the  $E_g$  values are listed in Table 1. The calculated band gap energy for sample SF11 Original is  $(2.15 \pm 0.02 \text{ eV})$  which is near to the band gap energy of sample SF11 Melted  $(2.09 \pm 0.02 \text{ eV})$ . For sample RSF14 Melted  $E_g$  was the highest obtained, at  $2.22 \pm 0.04 \text{ eV}$ , which

explains why it has the lowest *k-value* of the studied samples. Samples SF30 Melted and SF50 Melted have the same band gap energy ( $1.96 \pm 0.01$  eV). Despite the differences in hematite content of these samples, both have the same *k-value* of  $3 \times 10^{-3} \text{ min}^{-1}$ . This can be attributed to the differences in sizes of precipitated nanoparticles..

### 3.3. Enhancement of the photoactivity by the photo-Fenton reaction.

With the aim of obtaining enhanced performance, the photo-Fenton reaction has been applied. Hydrogen peroxide was added to 10 ml of MB solution; the concentration of  $\text{H}_2\text{O}_2$  in this solution was 0.34 M. As a result, higher *k-value* s were obtained: up to  $(2.8 \pm 0.08) \times 10^{-2} \text{ min}^{-1}$  and  $(2.2 \pm 0.07) \times 10^{-2} \text{ min}^{-1}$  for samples RSF14 Melted and SF11 Melted, respectively. Fig. 5 (solid lines) shows the pseudo-first-order rate constant of MB decomposition for all samples with the photo-Fenton experiment and associated *k*-values. It is noted that applying the photo-Fenton reaction halves the maximum degradation time, from 6 to 3 hours. This enhancement is mainly due to the photochemical reduction of  $\text{Fe}^{\text{III}}$  to  $\text{Fe}^{\text{II}}$ , and thus more  $\text{Fe}^{\text{II}}$  will be available to react with  $\text{H}_2\text{O}_2$  [11].

Brahmia reported that  $\text{TiO}_2$  can be used for MB degradation under UV light with *k-value* of  $33 \times 10^{-3} \text{ min}^{-1}$ [19]. The  $\text{TiO}_2$  polyacrylamide ( $\text{TiO}_2/\text{PAAm}$ ) hydrogel was used to remove MB from aqueous solution. Those results showed that about 95% of a 10 mg/L MB solution was photocatalytically degraded after 5 h under sunlight irradiation [20]. A  $\text{TiO}_2$  sol was prepared for the degradation of methylene blue (MB) solution under ultraviolet irradiation where the performance of 92.3% for colour removal was achieved after 160 min [21]. By comparison with the results we have obtained here,, it can be concluded that the prepared samples from slag can be a promising candidate as low-cost photocatalyst materials.

This work aims to prepare a catalyst with high degradation capability and low cost which can potentially be applied for wastewater treatment, so the sample SF11 Melted has been chosen for further study as it is simply melted slag with no need to add iron oxide, and the photo-Fenton reaction has been applied to this sample for the next investigation.

### **3.4. Parameters affecting the photocatalytic activity.**

#### **3.4.1. Catalyst Photoactivity under solar light irradiation:**

Using direct solar light is favourable for practical applications. Here, MB degradation under solar light irradiation was measured. The results, shown in Fig. 7, indicate an increase in  $k$ -value from  $(1.6 \pm 0.05)$ ,  $(2.2 \pm 0.07)$  and  $(3.4 \pm 0.1)$  to  $(3.5 \pm 0.2)$ ,  $(4.4 \pm 0.2)$  and  $(6.2 \pm 0.3) \times 10^{-2} \text{ min}^{-1}$  for catalyst loading of (2, 4 and 8 g / L), respectively. The obtained  $k$ -values in sunlight are almost double their values obtained using an irradiation source. This enhancement can be attributed to the existence of UV light in the solar spectrum which is not provided by the irradiation source, since a UV filter was placed in front of the irradiation source lamp [22].

#### **3.4.2. Effect of catalyst loading:**

One of the advantages of these catalysts is that the catalyst amount can be increased to a high value (due to high abundance and low cost), leading to an increase in degradation efficiency. In our case, the catalyst loading was varied from 2 to 64 g / L. The results of the degradation values as a function of catalyst loading are presented in Fig. 8. These show that the MB degradation, measured at 30 min, increases with catalyst loading from  $(24.0 \pm 0.5) \%$  for 2 g / L to  $(97 \pm 2) \%$  for 32 g / L. The increase in the degradation was due to the increase in the number of active surfaces on the catalyst per unit volume of MB [23], with an increase in the absorbed photons by the catalyst [24]. However, at 64 g / L, the degradation decreases: this is attributed to reductions in light which can reach to the catalyst as the solution opacity increases [25]. The optimum catalyst loading was found to be 32 g / L.

#### **3.4.3. The effect of initial dye concentration:**

To investigate the effects of dye concentration, the  $k$ -values were measured at different dye concentrations of 20, 40 and 60  $\mu\text{M}$ , and also at different catalyst loading levels simultaneously Fig. 9. It was found that, as the dye concentration increases, the  $k$ -value decreases; this is due to decreasing light penetrating the dye solution and reaching the catalyst as the solution gets darker and thus the formation of hydroxyl radicals is decreased since the dye molecules occupy the active sites of the catalyst [24, 20].

#### 3.4.4. The effect of solution temperature:

The degradation of MB solution at different temperatures of 30, 40, 50 and 60  $^{\circ}\text{C}$  was measured after 30 min of irradiation. The degradation at these temperatures was  $(37 \pm 2)$ ,  $(44 \pm 3)$ ,  $(74 \pm 4)$  and  $(94 \pm 6)$  %, respectively. Although the degradation increases as the temperature increases, this is due to the high temperature rather and not changes in photoactivity, as shown in Fig. 10. The degradation in the dark and blank samples also increased, especially at high temperature. The increase in degradation caused directly by temperature is due to increased mobility of hydroxyl radicals, leading to faster reaction with the dye molecules since the electron-hole pair recombination decreases [24, 25]. The same behaviour was observed by Mozia et al., in the case of azo dye Acid Red 18 [26], the degradation for blank or dark samples were not reported.

#### 3.4.5. Effect of $\text{H}_2\text{O}_2$ dosage:

The concentration of  $\text{H}_2\text{O}_2$  in MB solution was studied in the range from 0.08 to 0.68 M; the results are shown in Fig. 11. The highest  $k$ -value  $2.8 \times 10^{-2} \text{ min}^{-1}$  was obtained with  $\text{H}_2\text{O}_2$  dosage of 0.17 M. The enhancement of the degradation with increasing  $\text{H}_2\text{O}_2$  dosage is due to increased generation of hydroxyl radicals. Above 0.17 M, degradation decreases due to the excess  $\text{H}_2\text{O}_2$  encouraging  $(\text{HO}^{\bullet}_2)$  production and lowering  $^{\bullet}\text{OH}$  generation. It is also reported that excess of  $\text{H}_2\text{O}_2$  could generate  $^{\bullet}\text{OH}$ , which can dimerize to form  $\text{H}_2\text{O}_2$ , so this cumulative effect inhibits degradation [23].

### 3. 5. Catalyst stability:

The SF11 Melted and RSF14 Melted samples were reused under the same conditions for 7 times Fig. 12 with no cleaning or treatment of any kind in between subsequent experiments. The degradation was found to decrease by 5 and 15%, respectively, which is a promising result for reusing these catalyst materials, potentially leading to lower costs. It is important that these repeated measurements were carried out by simply centrifuging the solution then removing and replacing it with a new MB solution. No further filtration or drying of the powder was carried out, which is considered an advantage for easy and practical reusing.

## Conclusions

Slag-derived glass and glass-ceramic samples were successfully prepared by a melt-quench method, characterised, and then used as a photocatalytic material to decompose methylene blue dye under visible light and solar light irradiation. The photocatalytic activity of the prepared samples was found to obey the pseudo-first-order rate constant, having a  $k$ -value of  $3 \times 10^{-3} \text{ min}^{-1}$  for the samples SF30 Melted and SF50 Melted. In the photo-Fenton process, the  $k$ -values increased to  $2.8 \times 10^{-2} \text{ min}^{-1}$  and  $2.2 \times 10^{-2} \text{ min}^{-1}$  for the samples RSF14 Melted and SF11 Melted, respectively.

Irradiating sample SF11 Melted with direct solar light doubles the  $k$ -values up to  $4.4 \times 10^{-2} \text{ min}^{-1}$ . There is good correlation between the photocatalytic activity and the precipitated amount of hematite, while in the case of the photo-Fenton reaction, the degradation is mainly caused by paramagnetic iron  $\text{Fe}^{\text{III}}$  oxide. The optimum conditions for practical usage of the samples are using SF11 Melted sample in photo-Fenton reaction with 0.17 M of  $\text{H}_2\text{O}_2$  in sunlight with a maximum catalyst loading 32 g / L.

## Acknowledgments

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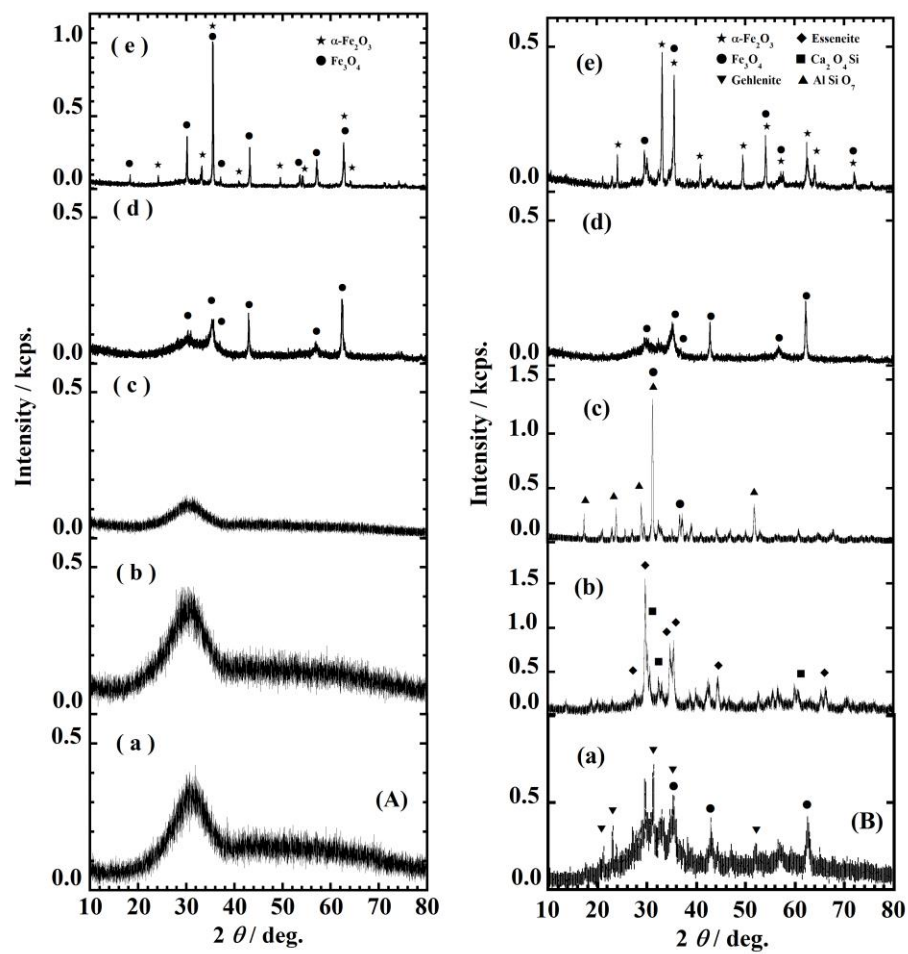
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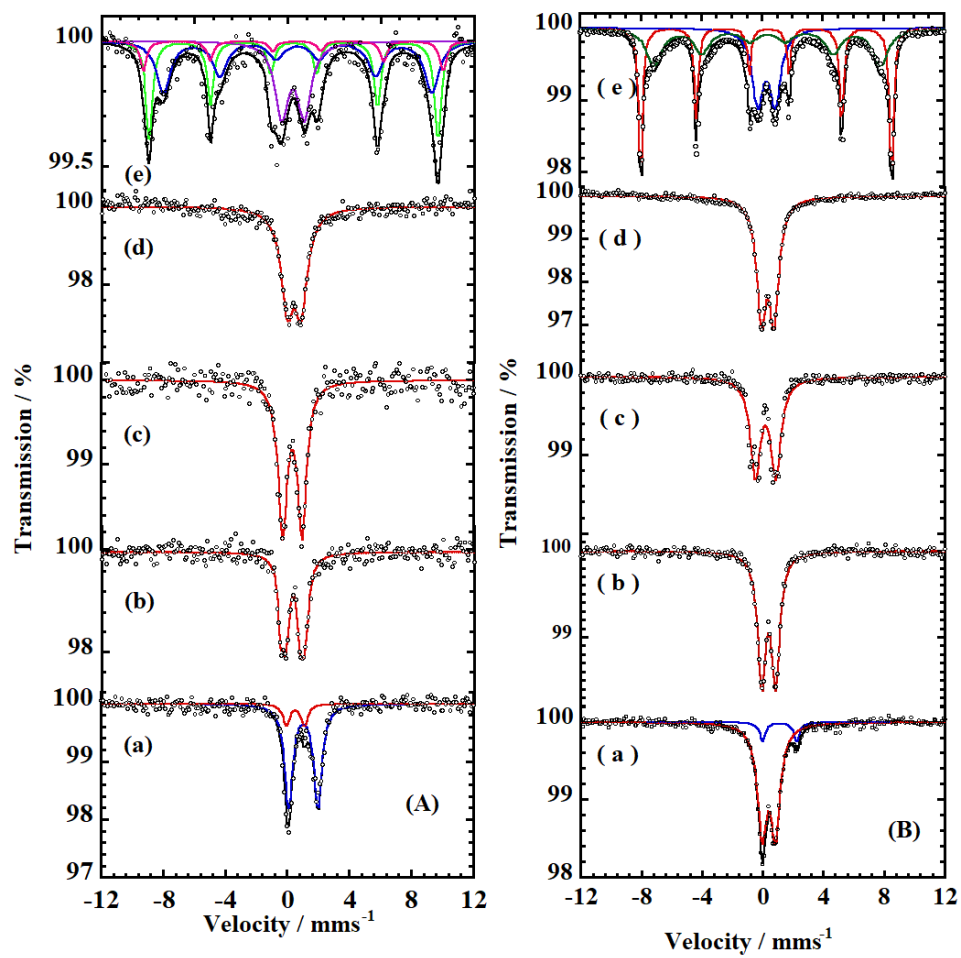
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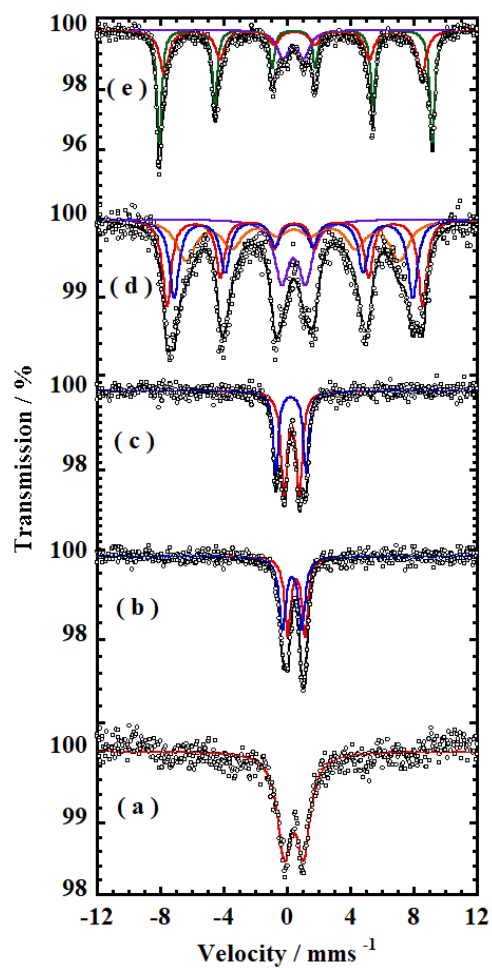
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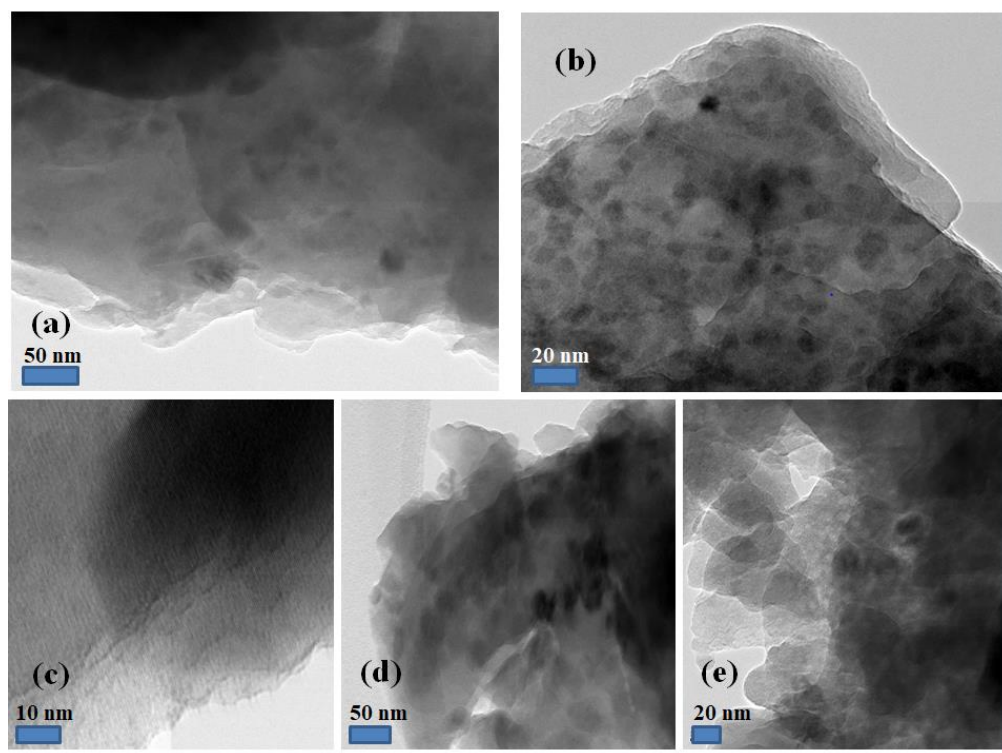
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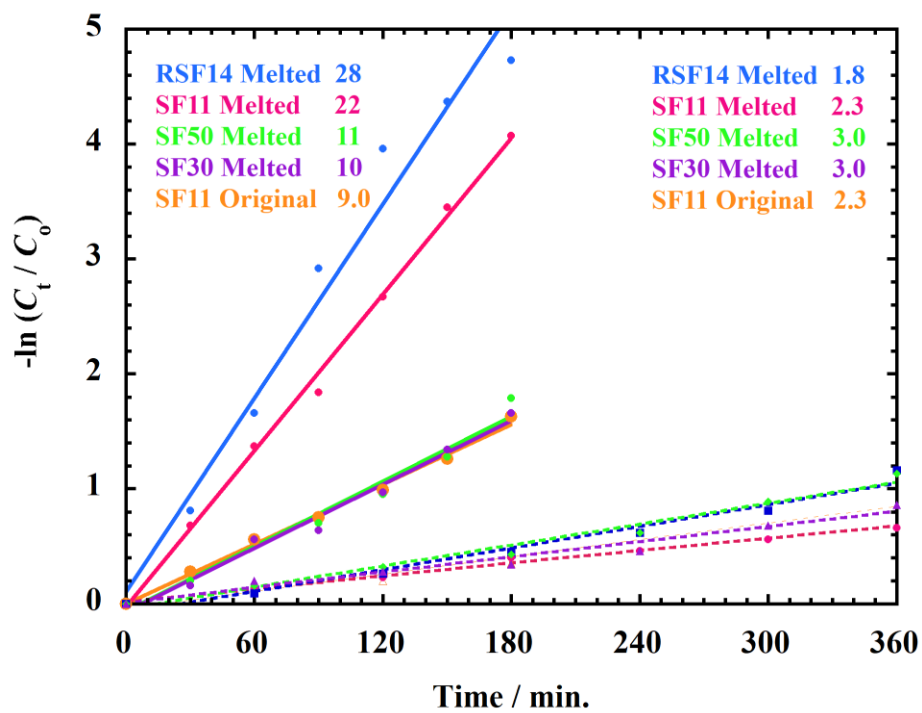
A. S. Ali *et al.*, Fig. 2 (A), (B)



A. S. Ali *et al.*, Fig. 3

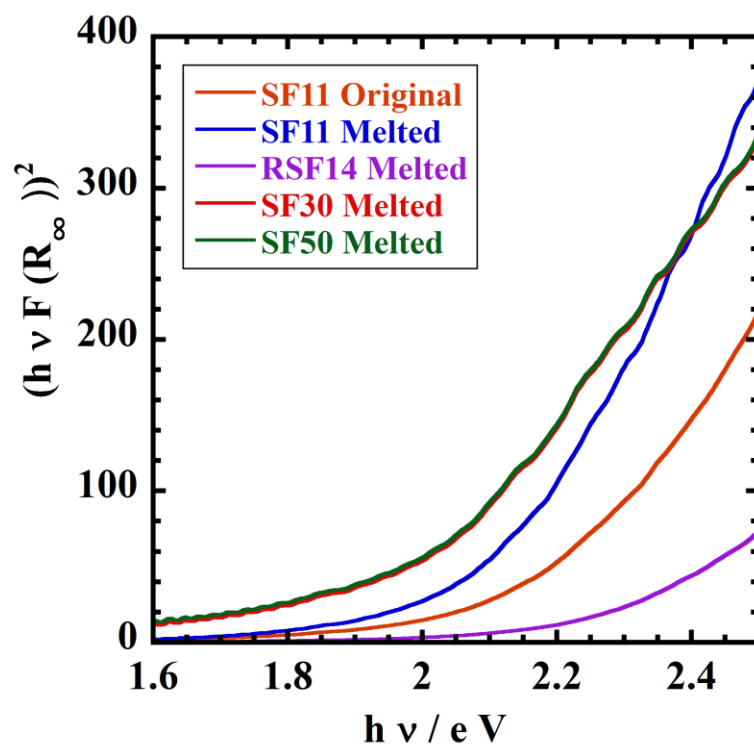


A. S. Ali *et al.*, Fig. 4

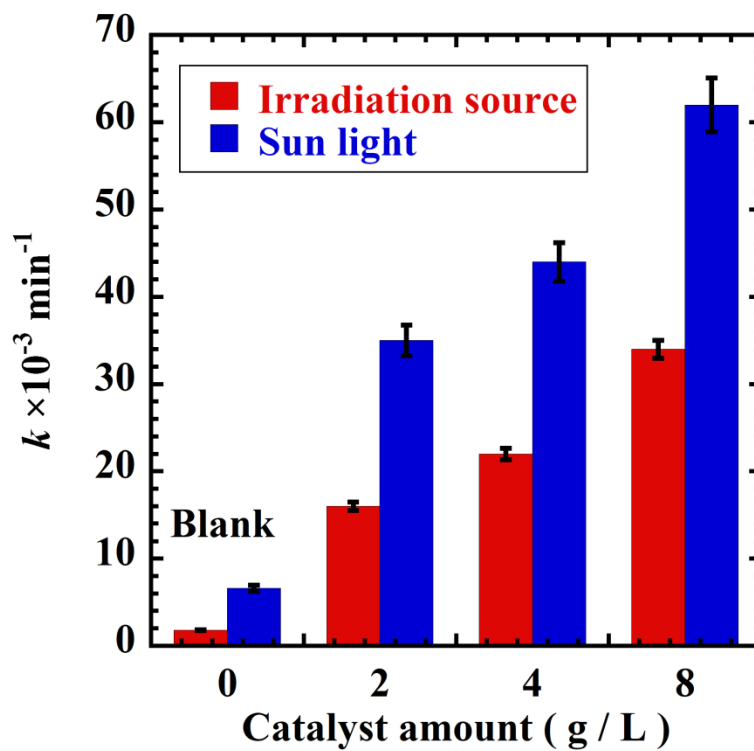


A. S. Ali *et al.*, Fig. 5

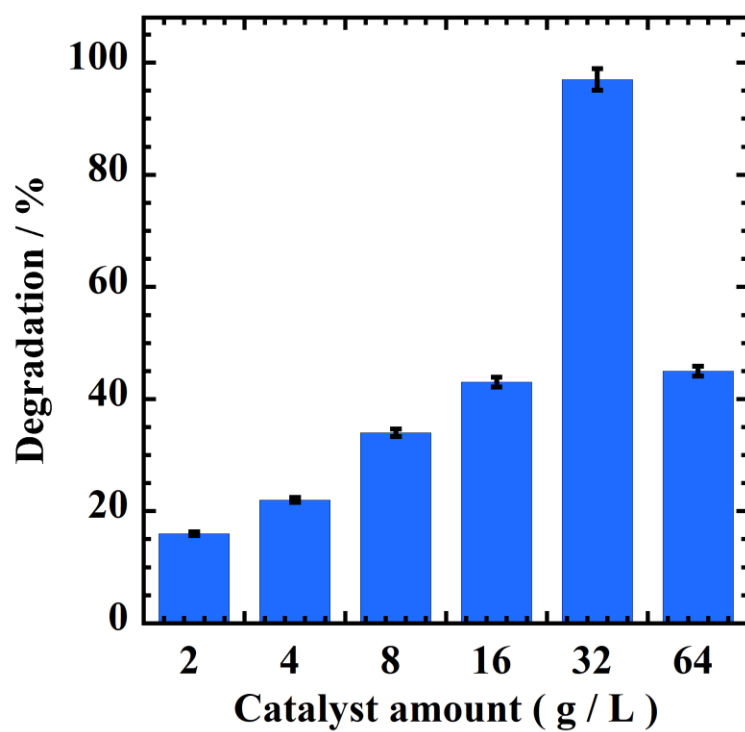




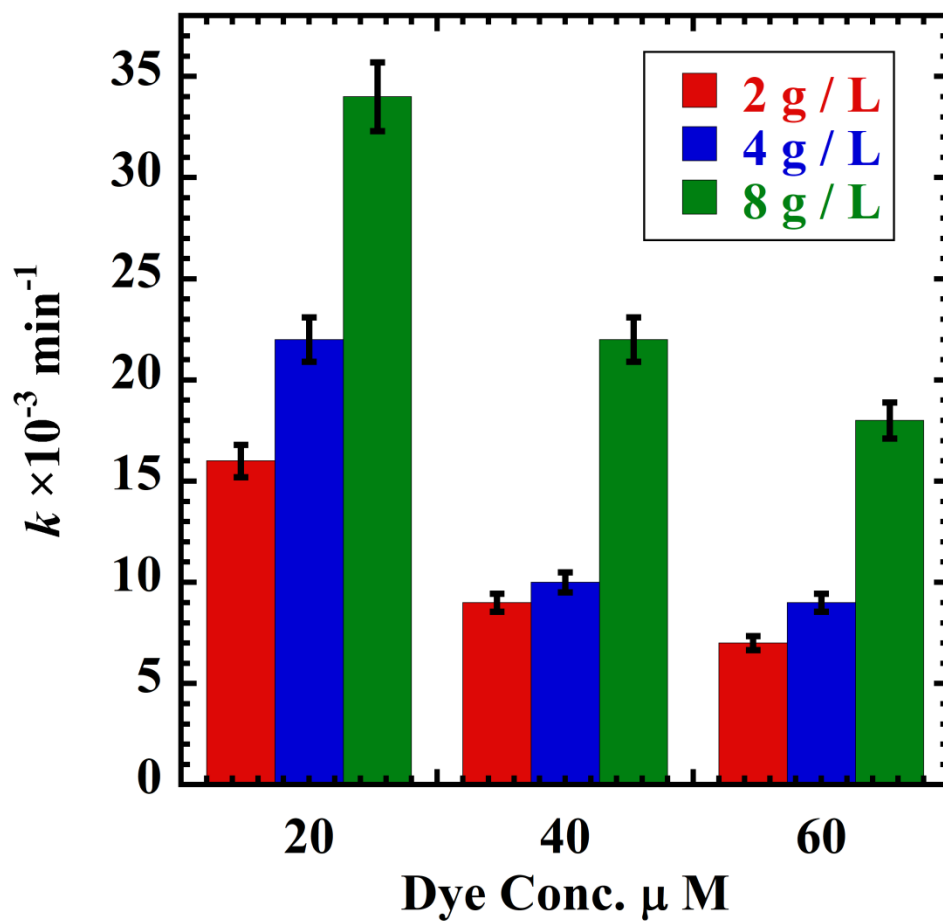
A. S. Ali *et al.*, Fig. 6



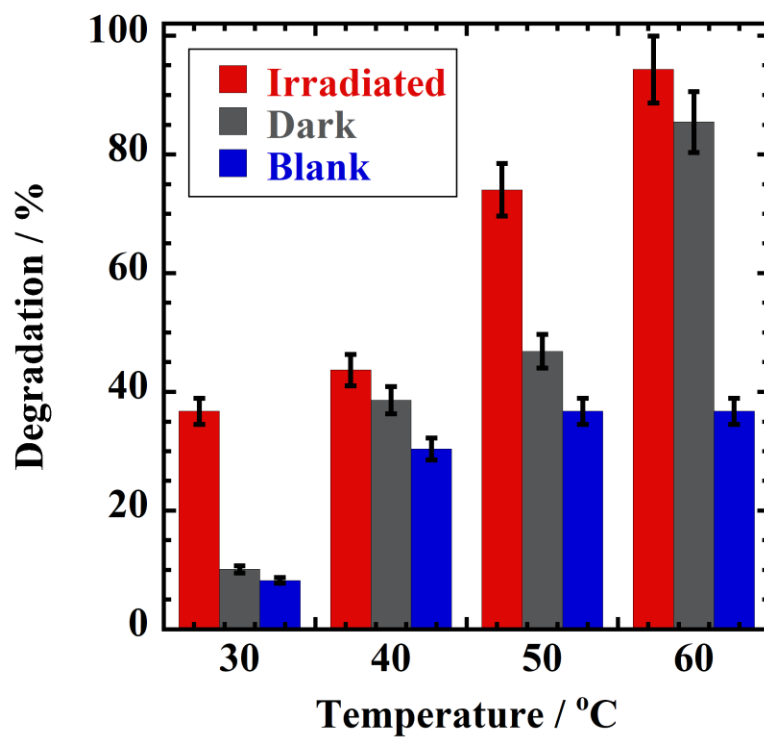
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A. S. Ali *et al.*, Fig. 8

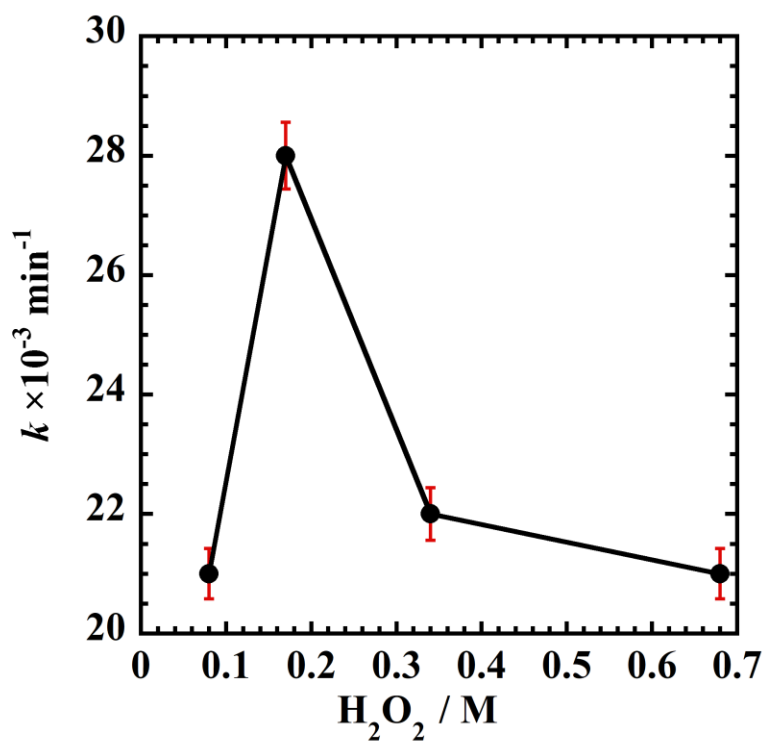


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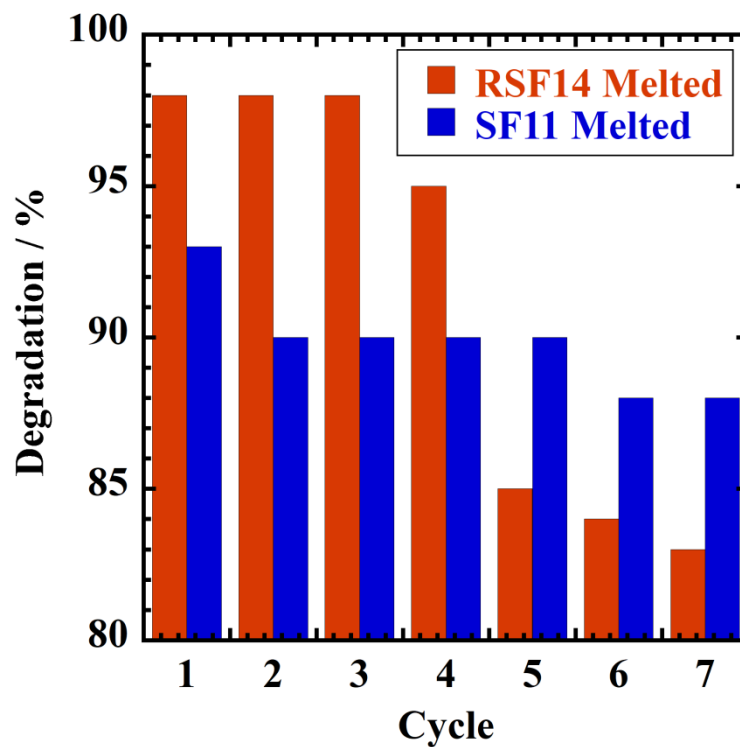


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100 A. S. Ali *et al.*, Fig. 10



A. S. Ali *et al.*, Fig. 11



A. S. Ali *et al.*, Fig. 12

Figure Captions

**Fig. 1** XRD patterns of slag samples (A) before and (B) after heat treatment at 800 °C for 100 min of (a) SF11 Original, (b) SF11 Melted, (c) RSF14 Melted, (d) SF30 Melted and (e) SF50 Melted

**Fig. 2** RT Mössbauer of slag samples (A) before and (B) after heat treatment at 800 °C for 100 min of (a) SF11 Original, (b) SF11 Melted, (c) RSF14 Melted, (d) SF30 Melted and (e) SF50 Melted

**Fig. 3** Mössbauer spectra measured at 77 K of slag samples after heat treatment at 800 °C for 100 min; (a) SF11 Original, (b) SF11 Melted, (c) RSF14 Melted, (d) SF30 Melted, (e) SF50 Melted

**Fig. 4** TEM images of slag samples of (a) SF11 Original, (b) SF11 Melted, (c) RSF14 Melted, (d) SF30 Melted, (e) SF50 Melted after heat treatment at 800 °C for 100 min

**Fig. 5** Kinetic dye degradation measurements of methylene blue for slag samples heat treated at 800 °C for 100 min solid lines is under photo Fenton and dotted lines under visible light

**Fig. 6** Tauc's plot for slag samples heat treated at 800 °C for 100 min

**Fig. 7**  $k$  values for SF11 Melted heat treated at 800 °C for 100 min using vis. light irradiation source (in red) and sunlight (in blue)

**Fig. 8** Effect of catalyst loading on the MB degradation for the sample SF11 Melted heat treated at 800 °C for 100 min

**Fig. 9** Effect of initial dye concentration on the MB degradation for the sample SF11 Melted heat treated at 800 °C for 100 min

**Fig. 10** Effect of temperature on the MB degradation of the sample SF11 Melted heat treated at 800 °C for 100 min



**Fig. 11** Effect of H<sub>2</sub>O<sub>2</sub> concentration on MB degradation of the sample SF11 Melted heat treated at 800 °C for 100 min with catalyst loading 4 g / L and MB conc. of 20 µM

**Fig. 12** Reuse measurements of the samples SF11 Melted and RSF14 Melted heat treated at 800 °C for 100 min

**Table 1** Fe<sub>2</sub>O<sub>3</sub> (batch) content and bandgap energy of heat-treated slag samples calculated from DRS

Sample	Total Fe <sub>2</sub> O <sub>3</sub> content (mass % )	E <sub>g</sub> (eV)
SF11 Original	11.45 ± 0.01	2.15 ± 0.02
SF11 Melted	11.45 ± 0.01	2.09 ± 0.02
RSF14 Melted	14.40 ± 0.01	2.22 ± 0.04
SF30 Melted	30.00 ± 0.01	1.96 ± 0.01
SF50 Melted	50.00 ± 0.01	1.96 ± 0.01

**Table 2**  $^{57}\text{Fe}$ -Mössbauer parameters at room temperature of slag glass samples before and after heat treatment at 800 °C for 100 min

	Sample	assignment	A (%)	$\delta$ (mm s <sup>-1</sup> )	$\Delta$ (mm s <sup>-1</sup> )	$H_{\text{int}}$ (T)	$\Gamma$ (mm s <sup>-1</sup> )
Before	SF50 Melted	mag + mgh	32.2	0.30 $\pm$ 0.01	-0.02 $\pm$ 0.02	48.10 $\pm$ 0.01	0.42 $\pm$ 0.03
		mag.	34.4	0.52 $\pm$ 0.02	0.00	44.80 $\pm$ 0.02	0.88 $\pm$ 0.10
		Fe <sup>III</sup> $T_d$	23.6	0.27 $\pm$ 0.02	1.21 $\pm$ 0.03	-	0.84 $\pm$ 0.05
		hem.	9.8	0.37 $\pm$ 0.03	-0.20 $\pm$ 0.01	49.96 $\pm$ 0.02	0.43 $\pm$ 0.04
	SF30 Melted	Fe <sup>III</sup> $O_h$	100.0	0.40 $\pm$ 0.01	0.89 $\pm$ 0.02	-	0.99 $\pm$ 0.03
	RSF14 Melted	Fe <sup>III</sup> $T_d$	100.0	0.31 $\pm$ 0.01	1.25 $\pm$ 0.02	-	0.69 $\pm$ 0.02
	SF11 Melted	Fe <sup>III</sup> $T_d$	100.0	0.33 $\pm$ 0.01	1.25 $\pm$ 0.01	-	0.69 $\pm$ 0.02
	SF11 Original	Fe <sup>II</sup> $T_d$	85.5	1.00 $\pm$ 0.01	1.89 $\pm$ 0.02	-	0.63 $\pm$ 0.02
		Fe <sup>III</sup> $O_h$	14.5	0.50 $\pm$ 0.02	1.16 $\pm$ 0.08	-	0.51 $\pm$ 0.10
After	SF50 Melted	Fe <sup>III</sup> $T_d$	25.5	0.31 $\pm$ 0.03	1.14 $\pm$ 0.01	-	0.89 $\pm$ 0.01
		hem.	38.1	0.37 $\pm$ 0.01	-0.18 $\pm$ 0.04	51.40 $\pm$ 0.01	0.34 $\pm$ 0.03
		mgh.	36.4	0.37 $\pm$ 0.01	-0.02 $\pm$ 0.01	46.40 $\pm$ 0.01	1.23 $\pm$ 0.02
	SF30 Melted	Fe <sup>III</sup> $T_d$	100.0	0.32 $\pm$ 0.02	0.84 $\pm$ 0.03	-	0.76 $\pm$ 0.01
	RSF14 Melted	Fe <sup>III</sup> $T_d$	100.0	0.18 $\pm$ 0.01	1.34 $\pm$ 0.01	-	0.78 $\pm$ 0.01
	SF11 Melted	Fe <sup>III</sup> $O_h$	100.0	0.38 $\pm$ 0.04	0.92 $\pm$ 0.01	-	0.63 $\pm$ 0.01
	SF11 Original	Fe <sup>II</sup> $O_h$	9.8	1.10 $\pm$ 0.02	2.25 $\pm$ 0.05	-	0.44 $\pm$ 0.06
		Fe <sup>III</sup> $O_h$	90.2	0.37 $\pm$ 0.01	0.88 $\pm$ 0.01	-	0.75 $\pm$ 0.01

hem.: Hematite, mag.: Magnetite, mgh.: Maghemite,  $T_d$ : Tetrahedra,  $O_h$ : Octahedra, A: Absorption area,

$\delta$ : Isomer shift,  $\Delta$ : Quadrupole splitting,  $H_{\text{int}}$ : Internal magnetic field,  $\Gamma$ : Line width.

**Table 3**  $^{57}\text{Fe}$ -Mössbauer parameters at 77 K of slag samples heat-treated at 800 °C for 100 min

sample	assignment	A (%)	$\delta$ (mm s <sup>-1</sup> )	$\Delta$ (mm s <sup>-1</sup> )	$H_{\text{int}}$ (T)	$\Gamma$ (mm s <sup>-1</sup> )
SF50 Melted	$\text{Fe}^{\text{III}} T_{\text{d}}$	14.1	$0.40 \pm 0.02$	$1.31 \pm 0.03$	-	$0.92 \pm 0.05$
	hem.	49.0	$0.48 \pm 0.01$	$0.13 \pm 0.01$	$53.50 \pm 0.01$	$0.37 \pm 0.01$
	mgh.	36.9	$0.43 \pm 0.01$	$-0.11 \pm 0.01$	$50.40 \pm 0.08$	$0.71 \pm 0.02$
SF30 Melted	$\text{Fe}^{\text{III}} T_{\text{d}}$	15.6	$0.41 \pm 0.02$	$1.50 \pm 0.03$	-	$1.05 \pm 0.05$
	Mag + mgh	27.9	$0.40 \pm 0.03$	$-0.08 \pm 0.05$	$41.90 \pm 0.40$	$1.40 \pm 0.10$
	hem.	28.1	$0.48 \pm 0.01$	$0.01 \pm 0.01$	$50.20 \pm 0.10$	$0.65 \pm 0.04$
	mag.	28.4	$0.42 \pm 0.01$	$-0.04 \pm 0.02$	$46.80 \pm 0.10$	$0.73 \pm 0.07$
RSF14 Melted	$\text{Fe}^{\text{III}} T_{\text{d}}$	58.5	$0.29 \pm 0.01$	$0.96 \pm 0.01$	-	$0.46 \pm 0.01$
	$\text{Fe}^{\text{III}} T_{\text{d}}$	41.5	$0.24 \pm 0.01$	$1.90 \pm 0.01$	-	$0.40 \pm 0.02$
SF11 Melted	$\text{Fe}^{\text{III}} O_{\text{h}}$	50.0	$0.58 \pm 0.01$	$1.09 \pm 0.01$	-	$0.46 \pm 0.03$
	$\text{Fe}^{\text{III}} T_{\text{d}}$	50.0	$0.32 \pm 0.02$	$1.21 \pm 0.02$	-	$0.50 \pm 0.03$
SF11 Original	$\text{Fe}^{\text{III}} T_{\text{d}}$	100.0	$0.42 \pm 0.01$	$1.20 \pm 0.01$	-	$1.03 \pm 0.03$

hem.: Hematite, mag.: Magnetite, mgh.: Maghemite,  $T_{\text{d}}$ : Tetrahedra,  $O_{\text{h}}$ : Octahedra, A: Absorption area,

$\delta$ : Isomer shift,  $\Delta$ : Quadrupole splitting,  $H_{\text{int}}$ : Internal magnetic field,  $\Gamma$ : Line width.