JST: Engineering and Technology for Sustainable Development
Volume 35, Issue 1, March 2025, 059-064

Investigating the Glass Properties when Using Electric Arc Furnace Dust as Coloring Agent

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Abstract

Electric Arc Furnace Dust (EAFD) and wasted glass are two types of waste in industry and daily life, so they must be recycled to recover some useful elements. The production of colored glass is one of the methods used to recycle the electric arc furnace dust to take advantage of the coloring element in the dust. To use this colored glass for decoration, it is also necessary to test its durability. The present study focuses on the properties of colored glass when using electric furnace dust. The investigation examines the chemical composition and phase structure of the colored glass, containing varying dust amounts of 0.5:99.5, 2:98, 5:95, 10:90, and 15:85. Using SEM-EDX analysis and compressive strength testing, the results show that changing the percentage of electric arc furnace dust in the glass makes a difference in its compressive strength. This change in strength is due to the distribution of dust particles within the glass matrix as a reinforced frame. Detailed discussion will be presented in the text section.

Keywords: Electric arc furnace dust, waste glass, color glass.

1. Introduction

The increasing industrial productions generate annually several tons of dust, slag, sludge, exhaust gases, and wastewater. Steelmaking using electric arc furnaces (EAFs) has become a prominent method in the steel industry, contributing significantly to global crude steel production. However, this process generates a notable byproduct known as electric arc furnace dust (EAFD), comprising approximately 1-2 wt.% of the steel produced [1-3]. EAFD is recognized for its hazardous components, including heavy metals like zinc, lead, cadmium, and chromium [4]. The improper disposal of EAFD poses environmental and health risks, with potential contamination of soil and water [5].

EAFD's chemical composition is complex and varies based on factors such as the type of scrap metal processed and furnace operating conditions. Typically, EAFD contains high levels of zinc oxide and significant amounts of iron oxide, calcium oxide, and silica [6]. These oxides play a pivotal role in influencing EAFD's physical and chemical properties, making it a potential candidate for recycling and reuse applications.

In recent years, there has been increasing interest in utilizing EAFD in the production of colored glass, offering a sustainable solution to address EAFD disposal challenges while adding value to glass production processes. Previous studies have explored incorporating EAFD into glass matrices, demonstrating its potential as a coloring agent due to the presence of several oxides [7-9]. For example, iron oxide in EAFD imparts various colors to glass, depending on its concentration and composition [10].

Moreover, recent research has highlighted the impact of EAFD inclusion on glass mechanical properties, such as compressive strength and toughness. The distribution of dust particles within the glass matrix significantly influences these properties, with higher EAFD concentrations associated with reduced compressive strength due to the formation of weaker phases within the glass structure [11].

Recycling electric furnace dust to recover useful elements or utilizing iron elements to reuse for iron and steel production are methods that have been applied and researched before. In a preceding study, the author adeptly demonstrated the fabrication of colored glass from electric arc furnace dust, without zinc reduction, employing varying masses of 0.5:99.5, 1:99, 2:98, 5:95, 10:90, 15:85, and without dust, amalgamated with waste glass. Building upon this foundation, the current investigation delves into the evaluation of compressive strength in the context of utilizing EAFD for colored glass production, supplemented by a meticulous analysis via Scanning Electron Microscopy coupled with Energy-Dispersive X-ray Spectroscopy (SEM-EDX), alongside the exploration of novel chromatic variations.

2. Experimental Procedures

Electric arc furnace dust provided by Thai Nguyen Iron and Steel JSC and collected waste glass have the chemical composition shown in Table 1 [12]

ISSN 2734-9381
https://doi.org/10.51316/jst.180.etsd.2025.35.1.8
Received: Aug 14, 2024; revised: Oct 21, 2024;
accepted: Dec 4, 2024

to determine the impact of EAFD on coloring ability and mechanical properties.

Table 1. Chemical composition of raw materials, %

Compound	EAFD	Wasted glass
Al_2O_3	0.60	0.94
CaO	3.15	7.03
Fe_2O_3	64.56	0.17
K_2O	1.16	-
Na_2O	0.44	16.57
MgO	1.43	4.15
MnO	3.40	-
SiO_2	3.97	70.72
Cr_2O_3	0.180	-
CuO	0.129	-
NiO	0.019	-
PbO	0.709	-
ZnO	11.31	-

After the initial crushing phase, the electric arc furnace dust (EAFD) and waste glass are intricately blended in specific mass ratios: 15:85, 10:90, 5:95, 2:98, 1:99, 0.5:99.5, and 0:100 (with no dust). Each sample was conducted under a heating rate of 20 ºC/min in an air environment up to 1400 ºC held for 30 minutes to ensure the glass melted completely and evenly with EAFD. Following this melting process, the molten mixtures are poured into designated molds, allowing them to cool and solidify into distinct glass samples. These produced glasses were analyzed for compressibility strength and morphology.

The compressive strength of the obtained colored glass samples was measured using a compressive strength tester model E45.105 (supported by the SAHEP project, Hanoi University of Science and Technology). When measuring, the samples all had the same dimensions (following the standard sizes).

SEM-EDX with JEOL JSM-6490 model was applied to observe the morphology of the samples and the dispersion of EAFD in the produced glass matrix.

Use the stress-strain diagram from the compressive strength experiment to calculate toughness.

The toughness is determined using the following formula:

$$\text{Toughness} = \int_0^{\varepsilon_f} \sigma \, d\varepsilon \quad (1)$$

where ε_f is ultimate deformation on the graph;

ε is extent of deformation;

and σ is stress

3. Results and Discussion

Fig. 1 shows the images of colored glasses produced with different EAFD contents. It is seen that the melting process at 1400 ºC in ambient air created colored glass with different EAFD content. The more dust there is, the darker the glass color is, from mint green to dark black. For instance, when incorporating 15:85 dust alongside 85% colorless waste glass to formulate black glass, a decrease in the dust amount to 10:90 initiates a nuanced transition from black to dark black [12, 13]. Each ratio of dust and glass gives the corresponding color as follows a) 0:100, a light blue hue emerges, while at b) 0.5:99.5, the color transitions to mint green. Increasing the ratio to c) 1:99 results in a green tint, which deepens to dark green at d) 2:98. The color shifts to moss green mixed with black at a ratio of e) 5:95. At f) 10:90 and g) 15:85, the glass takes on a dominant black hue. A clear relationship between the dust contcentration and the color was observed in the glass samples. It is shown that the ratio of dust and glass increases, so does the color density. This underscores the close interdependence between the ratio of dust and glass and the color diversity exhibited by the glass samples. It also can be seen that the dust particles are evenly dispersed on the glass substrate and some particles have not yet melted. The color produced in the electric furnace dust glass is due to the iron element [13]. When the dust content changes, the color of the glass also changes, meaning the iron content changes. The color range created here is determined by the color range of iron, specifically from mint green to black.

As shown in Fig. 2, the compressive curve of four distinct samples produced with varying mass percentages of dust and wasted glass (0.5:99.5, 1:99, 2:98, and 15:85), which is showcased. Through this detailed examination, we aim to unravel the nuanced relationship between the composition of these materials and their corresponding compressive strengths. This comprehensive analysis provides valuable insights into the mechanical properties of the glass samples, shedding light on their structure. It is seen that the study illustrates a discernible pattern: as the proportion of dust increases, the compressive strength and toughness of the samples tend to diminish. For instance, the peak compressive strength dwindles from 123 MPa with a mere 1% dust concentration to a mere 26 MPa when the dust content escalates to 15:85. This decline can be ascribed to the distribution of dust particles within the glass matrix, where impurities contribute to a reduction in the compressive strength of the specimen. Notably, the sample containing 1:99 dust manifests the highest compressive strength, while the lowest, at 26 MPa, corresponds to the sample with the highest dust content of 15:85. The compressive strengths of specimens with dust concentrations of 0.5:99.5 and 2:98 are registered at 103 MPa and 50 MPa, respectively. For two samples 0.5:99.5 and 1:99 on the stress-strain curve, only elastic deformation is seen without stress deformation. While the two samples 2:98 and 15:85 on the stress-strain curve receive additional plastic deformation. Thus, the plastic deformation process is determined by EAFD. EAFD acts as a skeleton that increases the strength of colored glass.

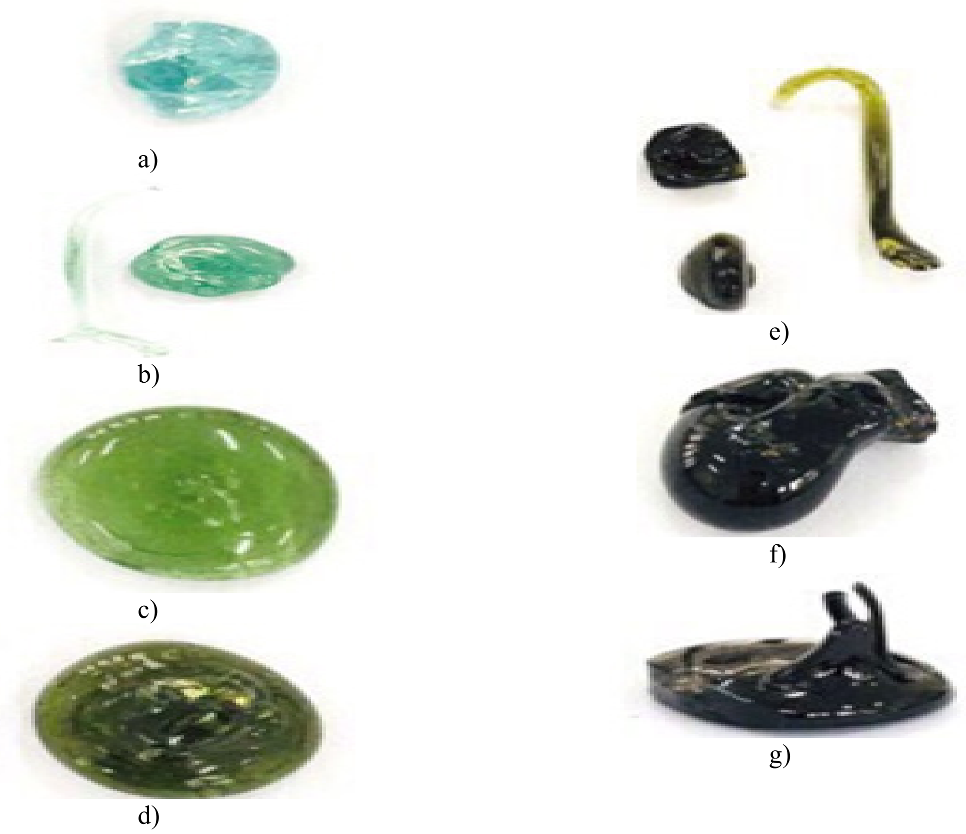
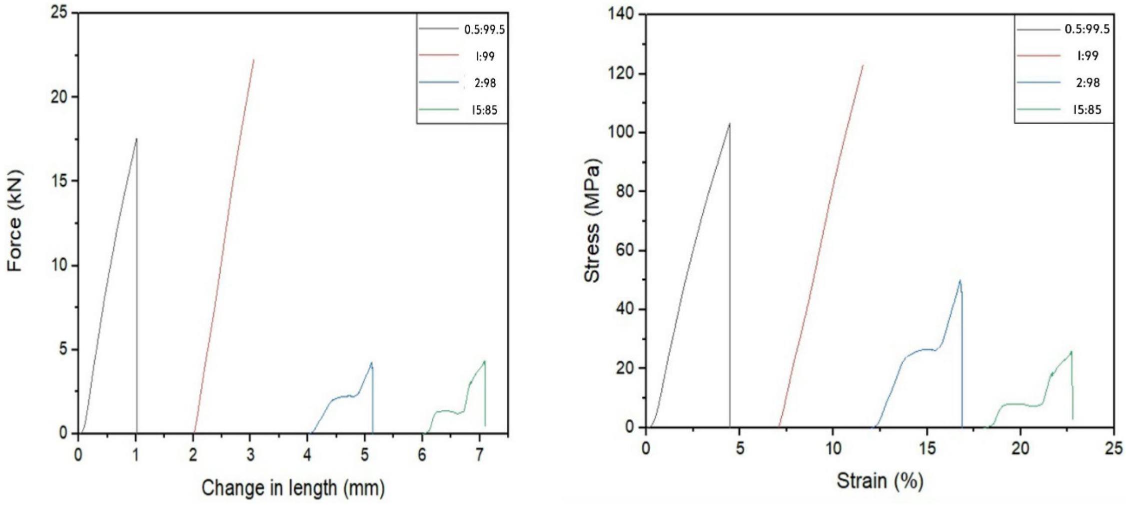


Fig. 1. Images of glass samples with different ratios of dust and glass

(a) 0:100; (b) 0.5:99.5; (c) 1:99; (d) 2:98; (e) 5:95; (f) 10:90; (g) 15:85



a) The relationship between force and change in length

b) The relationship between stress and strain

Fig. 2. The compression curves of four samples with different ratios of dust and glass.

Similarly, the toughness of the samples, determined by the area beneath the stress-strain curve, mirrors the trend observed in the compressive strength data. The highest toughness is evident in the sample with a 1:99 dust concentration, recording approximately 2.81 MPa $m^{-1/2}$. Conversely, the toughness values for samples with dust concentrations of 0.5:99.5, 2:98, and 15:85 are documented at 2.28, 1.21, and 0.43 MPa $m^{-1/2}$, respectively.

According to the calculation expression stated in Section 2. Experimental Procedures, Fig. 3 illustrates the scientific correlation between impact toughness and the varying dust percentage. The toughness is quantified by the integration of stress. This relationship demonstrates how the impact toughness of the material changes with different dust percentages, providing insights into the material's ability to absorb energy before fracturing. This figure allows for a detailed analysis of this correlation, highlighting the effects of dust content on the mechanical properties of the material. The sample with a ratio of dust and glass of 1:99 exhibits the highest toughness, approximately 2.81 MPa $m^{-1/2}$. Among the ratios tested to create colored glass, the ratio 1:99 gives the greatest durability compared to other ratios. It can be said that this ratio is the best ratio to create bright-colored glass for the highest durability. Comparing the other proportions, the sample with ratio of dust and glass of 0.5:99.5 shows the second-highest toughness at 2.28 MPa $m^{-1/2}$. The toughness further decreases with increasing dust content, the ratio of dust and glass of the 2:98 sample has a toughness of 1.21 MPa $m^{-1/2}$, and the sample with a 15:85 ratio exhibits the lowest toughness at 0.43 MPa $m^{-1/2}$. These comparisons highlight a significant inverse relationship between dust content and material toughness, demonstrating how increasing the proportion of dust adversely affects the mechanical properties of the glass. As mentioned above, EAFD acts as a skeleton for the glass substrate, increasing the toughness of colored glass. But when the dust content increases to 2%, the toughness decreases because the bond between the glass and dust particles may decrease [14-16].

In Fig. 4 the SEM/EDX of two samples containing 2:98 and 15:85 electric arc furnace dust (EAFD). That is the distribution of dust particles within the glass matrix. The presence of dust particles in glass increases the mechanical properties of colored glass, it acts as a reinforcing frame for the glass to be more durable. But when it increases further, the bond between glass and dust decreases, causing durability to decrease. The SEM capture arrow marker is believed to be the EAFD particle site due to the zinc content in the EDX spectrum. The distribution of EAFD particles on the glass substrate can be seen when more EAFD (b) is used on the sample using less EAFD (a). The number and distribution of EAFD particles affect the toughness of colored glass.

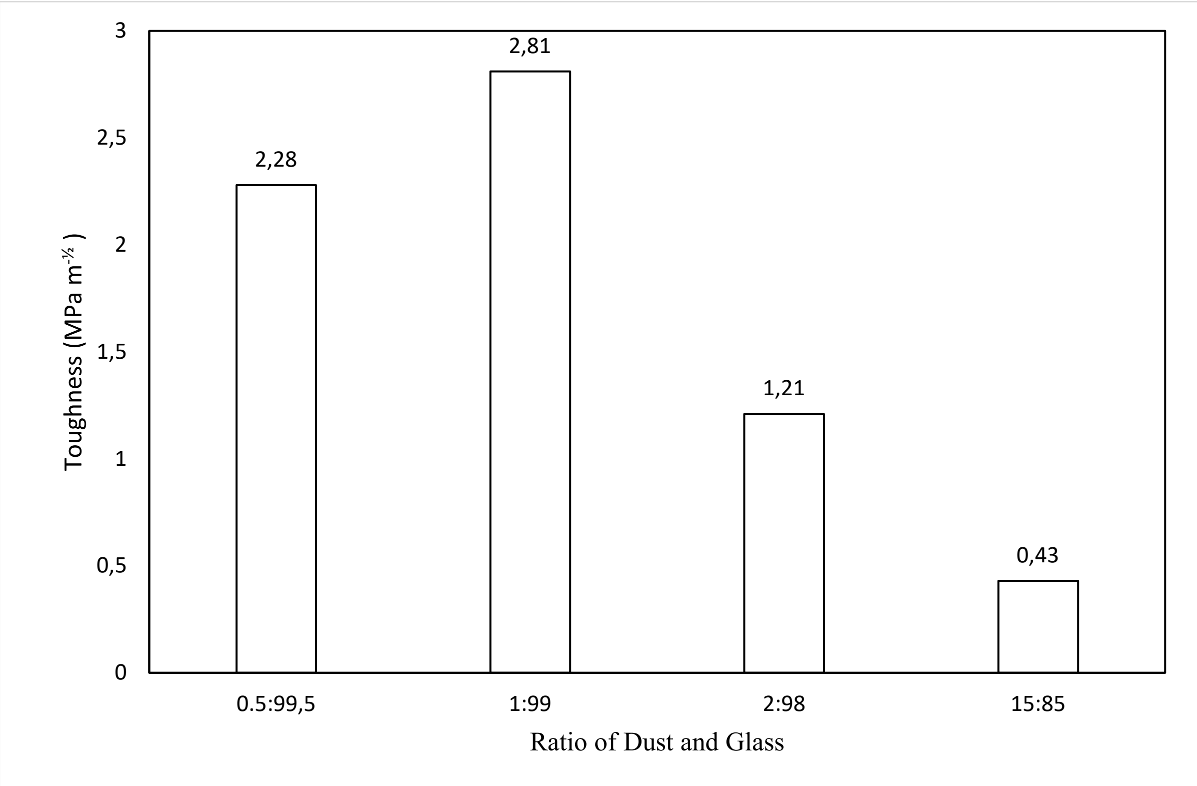
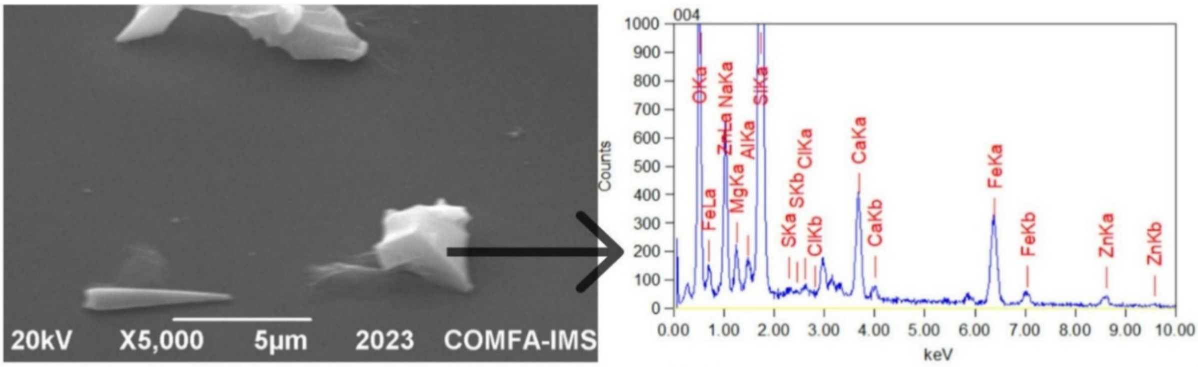
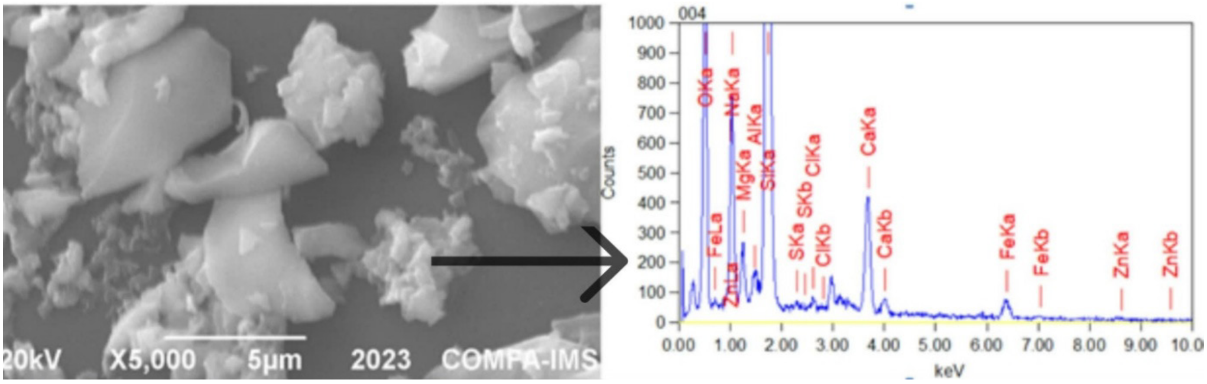


Fig. 3. The scientific correlation between impact toughness and the varying ratio of dust and glass



(a)



(b)

Fig. 4. The SEM/EDX of the samples with a ratio of dust and glass ratio is (a) 2:98 and (b) 15:85

Table 1. Chemical compositions of samples 15:85 dust and 2:98 dust in mass

Chemical composition, %									
Dust: glass ratio	Na_2O	MgO	Al_2O_3	SiO_2	CaO	Fe_2O_3	ZnO	Other	Total
15:85	7.89	3.04	2.41	60.12	6.75	15.66	3.37	0.77	100
2:98	9.8	3.41	2.3	72.49	7.48	3.2	0.27	1.06	100

Table 1 presents the detailed chemical composition of two glass samples with ratios of dust and glass of 15:85 and 2:98.

In the chemical components, the content of Fe_2O_3, ZnO, and SiO_2 changed a lot in the two samples, specifically for Fe_2O_3 from 3.2 to 15.66%, ZnO from 0.27 to 3.37% and SiO_2 from 60.12 to 72.49%, while the other components did not change much like MgO, CaO, and Al_2O_3. Fe_2O_3 is the most variable component. It is the cause of the change in color of glass containing EAFD. This also means that changing the chemical composition content can change the color and the toughness of colored glass.

4. Conclusion

The research successfully manufactured colored glass containing electric furnace dust in varying ratios of 0.5:99.5, 1:99, 2:98, 5:95, 10:90, and 15:85. The resulting colors included mint green, green, dark green, most green with black, and black for the highest ratios of dust and glass.

When incorporating electric furnace dust, the colored glass exhibited increased toughness properties with the best durability observed at the ratio of dust and glass at 1:99, this ratio provided the highest durability and an attractive, uniform color, making it suitable for industrial applications.

Acknowledge

The authors would like to thank Thai Nguyen Iron and Steel JSC for supplying the EAFD material.

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