

# Laboratory Studies on the Effect of End-of-Life Rubber Tyre Blending with Metallurgical Coke on Slag Foaming in Electric Arc Furnace Steelmaking\*

<sup>1</sup>J. R. Dankwah

<sup>1</sup>University of Mines and Technology, Tarkwa, Ghana

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## Abstract

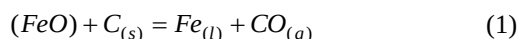
Currently, less than 20% of end-of-life rubber tyres (ELTs) are recycled globally and it has been estimated that 4 billion ELTs are currently held in various stockpiles across the globe. In this work the effect of ELT blending with metallurgical coke on slag foaming phenomena in the electric arc furnace (EAF) was investigated in a laboratory scale horizontal tube furnace through the sessile drop approach. Cylindrical substrates of carbonaceous materials were formed from a Drop Tube Furnace-treated metallurgical coke and its blends with ELT. The substrates were then used for slag foaming studies in a horizontal tube furnace by measuring the ratio ( $V_t/V_o$ ) of volume at time  $t$  ( $V_t$ ) to the initial volume ( $V_o$ ) as a function of time for various blends, using 0.065 g of pulverised EAF slag (47.1 wt % FeO). The results showed improvement in slag foaming with ELT blending, based on the measured values of ( $V_t/V_o$ ). Slag foaming therefore presents another avenue for recycling the billions of ELTs currently disposed of illegally or held in various stockpiles across the Globe.

**Keywords:** End-of-Life Rubber Tyre, Slag Foaming, Sessile Drop, Volume Ratio, Drop Tube Furnace

## 1 Introduction

In metallurgical practice, slag foaming is the expansion in the volume of molten slag due to the production of CO from the reduction of dissolved FeO by injected carbonaceous matter. Slag foaming is commonly used in electric arc furnace (EAF) steelmaking to allow for long arc operation when the charge is nearly melted resulting in higher power input and, consequently, higher productivity (Corbari *et al.*, 2009).

The process is initiated by injecting a carbonaceous material, such as char or coal, into the slag, which then reacts with FeO dissolved in the slag producing CO, as shown in Equation 1 (Corbari *et al.*, 2009). This phenomenon causes the slag to foam.



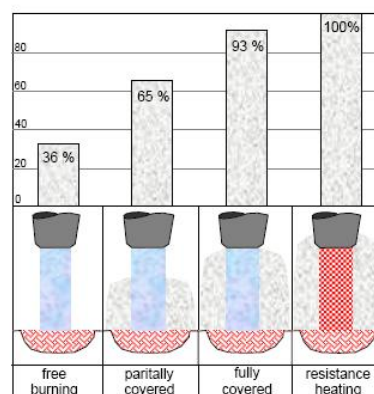
If the injected carbonaceous material (e.g. coal, polymer, etc.) contains volatiles, the volatiles released from it may also aid foaming. Foamy slag practice is an important phenomenon in steelmaking owing to several advantages often attributed to it. Among these advantages are:

- (i) It shields molten steel against atmospheric oxidation
- (ii) It acts as a thermal barrier to prevent heat losses

- (iii) It shields the refractory lining particularly in electric arc furnace
- (iv) It controls heat transfer from the post combustion flame

Ameling and Petry (1986) touched on the influence of slag foaming on the efficiency of power input as shown in Fig. 1, where the efficiency increases from 36% for free burning through 93% for a fully covered electrode to 100% for resistance heating.

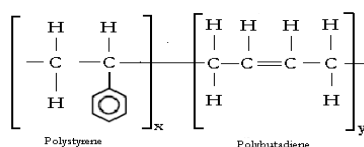
An obvious consequence of slag foaming is the reduction in electrical energy consumption, which is a critical parameter in the economy of electric arc furnace steelmaking.



**Fig. 1 Influence of Slag Foaming on the Efficiency of Power Input (Modified after Ameling *et al.*, 1986)**

Accordingly, slag foaming has become a popular area for investigation among various researchers (Ito and Fruehan, 1989; Lotun and Pilon, 2005; Corbari *et al.*, 2009; Sahajwalla *et al.*, 2009; Zaharia *et al.*, 2009; Rahman *et al.*, 2009; Kongkarat *et al.*, 2012;).

An emerging feature of the research in this area is the effect of hydrogen on slag foaming phenomena, which has culminated in the use of volatile-producing carbonaceous materials like coal (Corbari *et al.*, 2009) and waste polymers (Sahajwalla *et al.*, 2009; Zaharia *et al.*, 2009; Kongkarat *et al.*, 2012; Rahman *et al.*, 2009). One waste polymer that is readily available and has significant amounts of carbon and hydrogen is ELT. Its structure is illustrated in Fig. 2, which shows ELT as a copolymer of polystyrene and polybutadiene.



**Fig. 2 Structure of Styrene Butadiene Copolymer**

**Table 1 Proximate Analysis of ELTs.**

| Author                            | Component (wt %) |              |          |       |       |
|-----------------------------------|------------------|--------------|----------|-------|-------|
|                                   | Volatile         | Fixed Carbon | Moisture | Ash   | Steel |
| Juma <i>et al.</i> , (2006)       | 61.61            | 22.66        | 1.72     | 14.01 | -     |
| Rodrigues <i>et al.</i> , (2001)  | 58.8             | 27.7         | -        | 3.9   | 9.6   |
| Lee <i>et al.</i> , (1995)        | 67.3             | 28.5         | 0.5      | 3.7   | -     |
| Chang (1996)                      | 62.32            | 26.26        | 1.31     | 10.29 | -     |
| Gonzales <i>et al.</i> , (2001)   | 61.9             | 29.2         | 0.7      | 8.0   | -     |
| Chen <i>et al.</i> , (2001)       | 93.73**          | -            | 0.54     | 5.3   | -     |
| Loresgoiti <i>et al.</i> , (2004) | 59.3             | 27.6         | -        | 3.5   | 9.6   |
| Orr <i>et al.</i> , (1996)        | 68.7             | 23.3         | 0.4      | 7.6   | -     |
| Williams and Bottrill, (1995)     | 66.5             | 30.3         | 0.8      | 2.4   | -     |
| Atal and Levendis, (1995)         | 58.7             | 33.6         | -        | 7.7   | -     |

**Table 2 Elemental Analysis of ELTs.**

| Author                            | Component (wt %) |      |      |      |      |       |
|-----------------------------------|------------------|------|------|------|------|-------|
|                                   | C                | H    | N    | S    | O    | Ash   |
| Rodrigues <i>et al.</i> , (2001)  | 74.2             | 5.8  | 0.3  | 1.5  | 4.7  | 13.5  |
| Juma <i>et al.</i> , (2006)       | 81.24            | 7.36 | 0.49 | 1.99 | 8.92 | -     |
| Lee <i>et al.</i> , (1995)        | 83.8             | 7.6  | 0.4  | 1.4  | 3.1  | 3.7   |
| Chang (1996)                      | 74.4             | 6.96 | 0.21 | 1.6  | 5.02 | 10.21 |
| Gonzales <i>et al.</i> , (2001)   | 86.7             | 8.1  | 0.4  | 1.4  | 1.3  | 2.9   |
| Chen <i>et al.</i> , (2001)       | 81.16            | 7.22 | 0.47 | 1.64 | 2.07 | 7.44  |
| Berrueco <i>et al.</i> , (2005)   | 88.5             | 6.6  | 0.4  | 1.6  | 3.0  | -     |
| Arion <i>et al.</i> , (2001)      | 73.8             | 5.3  | 0.44 | 1.71 | 0.11 | 17.8  |
| Loresgoiti <i>et al.</i> , (2004) | 74.2             | 5.8  | 0.3  | 1.5  | 5.1  | 13.1  |
| Orr <i>et al.</i> , (1996)        | 81.3             | 7.3  | 0.3  | 1.5  | -    | 1.4   |
| Williams and Bottrill (1995)      | 85.8             | 8.0  | 0.4  | 1.0  | 2.3  | 2.4   |
| Lanoir <i>et al.</i> , (1997)     | 82.63            | 7.5  | 0.36 | 1.69 | -    | -     |
| Senneca <i>et al.</i> , (1999)    | 86.7             | 6.9  | 0.3  | 1.9  | 1.0  | 3.3   |
| Roy <i>et al.</i> , (1997)        | 86.6             | 8.1  | 0.5  | 0.8  | 2.2  | -     |
| Cunliffe and Williams (1998)      | 86.4             | 8.0  | 0.5  | 1.7  | 3.4  | 2.4   |

Currently, less than 20% of ELTs are recycled globally and it has been estimated that 4 billion ELTs are currently held in stockpile across the globe with over a billion units added annually (Dankwah and Koshy, 2013). Large stockpiles of ELTs are a risk to human health and the environment. This is because they provide breeding grounds for disease-carrying mosquitoes and rodent and also could catch fire from lightning strikes or even arson (Dankwah and Koshy, 2013).

Work done by previous researchers (Tables 1 and 2) have shown that ELTs contain significant amounts of both carbon and hydrogen that can be salvaged for reduction of iron oxides and also for inducing slag foaming in EAF steelmaking (Zaharia *et al.*, 2009; Dankwah *et al.*, 2012; Dankwah and Koshy, 2013).

Juma *et al.*, (2006) investigated the pyrolysis of ELT and observed that the products of ELT pyrolysis process comprised 30-40 wt% solid char, 40-60 wt% liquid residue, and 5-20 wt% gases. Whilst the solid residue contained carbon black and the mineral matter initially present in the tyre and the liquid fraction consisted of a complex mixture of organic compounds containing a lot of aromatics, the gaseous fraction was comprised of non-condensable organics such as, H<sub>2</sub>, H<sub>2</sub>S, CO, CO<sub>2</sub>, CH<sub>4</sub>, C<sub>2</sub>H<sub>4</sub> and C<sub>3</sub>H<sub>6</sub>. Apart from CO<sub>2</sub>, all the non-condensable organics are potent reducing agents for iron oxide reduction.

Industrially, the use of ELTs in the EAF has been documented in a case study by Clauzade (2006). In that case study the injection of ELTs in the furnace led to an exothermic phenomenon that increased the temperature within 5-10 minutes after the injection. In these trials, the ELTs were charged wholly at a rate of 1.7 kg ELT per kg of carbon and the off-gas (CO and H<sub>2</sub>) levels increased by 10-20% (Clauzade, 2006; Dankwah and Koshy, 2013).

The constitution of the molten slag is such that it is easier for the gases (formed from the reaction of the dissolved FeO and the carbonaceous materials) to escape vertically, rather than sideways. Accordingly, the height of the foam is critical and it has been one important property often targeted by researchers for slag foaming studies. Ito and Fruehan (1989) demonstrated that the foam height  $H_f$  (m) was proportional to the rate of gas generation  $Q$  (m<sup>3</sup>/s), with the proportionality constant termed as the foam index  $\Sigma$  (seconds), Equation (2):

$$H_f = \frac{\Sigma Q}{A} \quad (2)$$

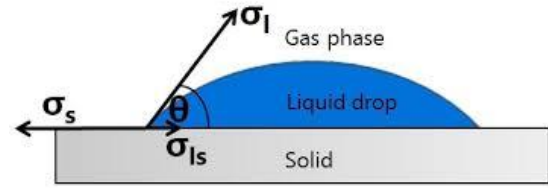
The foam height  $H_f$  is related to the superficial gas velocity  $V_g$  (m/s) and the cross-sectional area of the foam  $A$  (m<sup>2</sup>) (Corbari *et al.*, 2009), Equations (3) and (4):

$$H_f = \Sigma V_g \quad (3)$$

$$V_g = \frac{Q}{A} \quad (4)$$

Using the sessile drop approach for studies into slag-carbon interfacial reactions, Sahajwalla *et al.*, (2009) showed that the progress of a foamy slag can be monitored by continuous measurement of volume ratio ( $V_t/V_o$ ) as a function of time, where  $V_t$  is the volume of the spherical slag droplet at time  $t$  and  $V_o$  is the initial volume. The ability of the molten slag to wet the surface of the carbonaceous substrate and, accordingly, the

contact angle  $\theta$  (Fig. 3) are also important parameters in slag foaming.



**Fig. 3 Illustration of Equilibrium Sessile Drop System.**

In this investigation, the effect of ELT blending with metallurgical coke on slag foaming is investigated in a custom made horizontal tube furnace at 1550 °C through measurements of  $V_t/V_o$ .

## 2 Resources and Methods Used

Metallurgical coke (received from OneSteel Sydney Mill, Australia) and its blends with ELT (passenger car tyre) in four different proportions were used as the carbonaceous material for this investigation. EAF slag (47.1 wt% FeO) from OneSteel Sydney Mill, Australia was used as the source of iron oxide. Its composition is shown in Table 3. The EAF slag is obviously very basic with a calculated basicity, B3 = 1.66.

**Table 3 Composition (XRF) of EAF Slag Utilised for the Investigation.**

| Component                                                                | Composition (%) |
|--------------------------------------------------------------------------|-----------------|
| CaO                                                                      | 24.1            |
| FeO                                                                      | 47.1            |
| Al <sub>2</sub> O <sub>3</sub>                                           | 4.9             |
| SiO <sub>2</sub>                                                         | 9.6             |
| MgO                                                                      | 10.2            |
| MnO                                                                      | 4.8             |
| Basicity B3 = %CaO/(%SiO <sub>2</sub> +%Al <sub>2</sub> O <sub>3</sub> ) | 1.66            |

### 2.1 Samples Preparation

The coke was ground and sieved to a particle size in the range of 0.45-0.47 mm. The ELTs were cut into crumbs of mean diameter of 4 mm followed by cryogenic grinding (i.e. grinding after immersing in liquid nitrogen) to particle size 0.45-0.47 mm, similar to that of coke. The carbonaceous samples were devolatilized and heat treated at 1200 °C in a laboratory Drop Tube Furnace (DTF) (Model HT VTF (Radatherm Pty. Ltd.)) with operating temperatures up to 1650 °C before being pulverised for substrate formation. The DTF is specially designed to simulate the conditions experienced by the combustion of carbonaceous materials in EAF steelmaking. The photo and schematic diagram of the DTF used in

this investigation are shown in Figs. 4 and 5, respectively, while its optimised experimental conditions are given in Table 4.

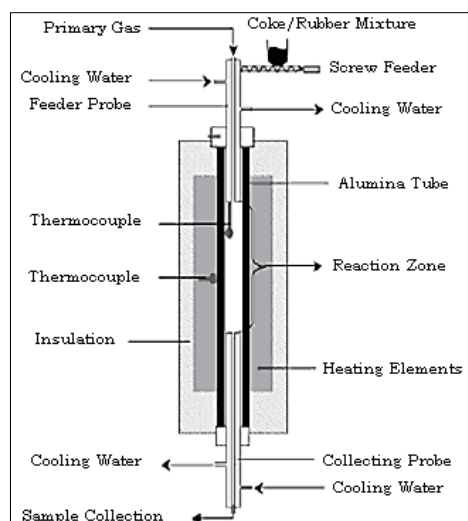
The DTF consists of a feeding system (Schenck AccuRate, Whitewater, Wisconsin), a sampling probe, an electrically heated furnace and a gas distribution system.



**Fig. 4 Photo of the Drop Tube Furnace (DTF) used for Devolatilisation Studies.**

The furnace is equipped with two type-B thermocouples; an external and internal thermocouples used for furnace ramping and improved response, respectively, during the measurements. Two gas inlets are present to admit  $N_2$  and  $O_2$ .  $N_2$ , which represents the main gas, is used to carry the solid reactants into the reaction zone and the secondary gas flow which contains the gaseous reactant,  $O_2$ , is designed to meet the primary gas flow at the tip of the water cooled injector.

The DTF is also equipped with three mass flow controllers, which are used to adjust flow rate and composition of both flows. Samples of ELT and commercially available steelmaking metallurgical coke (OneSteel Ltd., Sydney, Australia) are mixed and injected into the DTF through a dry material screw feeder.



**Fig. 5 Schematics of the Drop Tube Furnace (DTF) used for Devolatilisation Studies.**

**Table 4 Operating Conditions of the DTF Utilised for this Investigation.**

| Operating Parameters    | Values/Conditions                           |
|-------------------------|---------------------------------------------|
| Temperature             | 1200 °C                                     |
| Carbonaceous materials  | Met coke (OneSteel Ltd., Sydney, Australia) |
| Wastes polymer          | ELT- (Styrene Butadiene Rubber)             |
| Particle size           | 450-470 $\mu m$                             |
| Material injection rate | 0.05 g/sec                                  |
| Gas composition         | 20% $O_2$ ; 80% $N_2$                       |
| Gas flow rate           | 1.00 L/min                                  |
| Residence time          | 1-2 sec                                     |
| Heating rate            | 104 K/sec                                   |

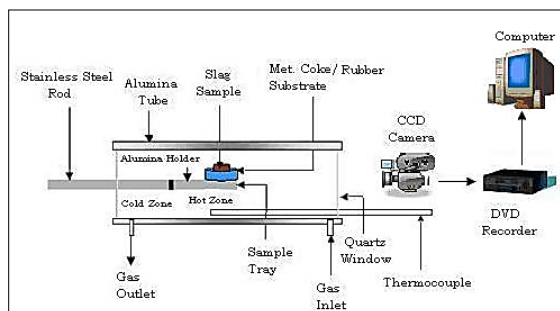
## 2.2 Experimental System and Procedure

The sessile drop approach was used to investigate carbon/slag interactions in an electrically heated laboratory-scale horizontal tube furnace (HTF), as shown in Figs. 6 and 7 for the photo and schematic diagram of the experimental setup, respectively. The furnace tube has an inner diameter of 50 mm and was fabricated from double-walled, vacuum-insulated stainless steel tubes fitted with a cooling fan to dissipate heat. The HTF is a micro scale reactor suitable for temperatures up to 1700 °C and equipped for high temperature metallurgical operations like the carbon/slag interactions that take place in EAF steelmaking. The operating parameters are presented in Table 5.





**Fig. 6 Photo of Laboratory Horizontal Tube Furnace utilised for the Investigation.**



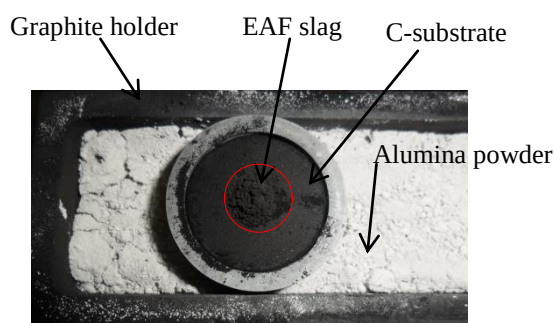
**Fig. 7 Slag Foaming/Reduction Studies using the Sessile Drop Technique in a Horizontal Tube Furnace.**

**Table 5 Operating Conditions of the HTF utilised for slag foaming studies.**

| Operating Parameters | Values/Conditions                       |
|----------------------|-----------------------------------------|
| Temperature          | 1550 °C                                 |
| Substrate Mass       | 1.6 g                                   |
| Slag                 | EAF slag (47.1 wt % FeO), OneSteel Ltd. |
| Slag Mass            | 0.065 g                                 |
| Substrate Area       | 1 cm <sup>2</sup>                       |
| Argon Flow rate      | 1.00 L/min                              |
| Duration             | 30 min                                  |

The carbonaceous residue collected after heat treatment in the DTF was milled for 1 minute in a ring mill pulveriser. The milled residue was weighed and compacted into a cylindrical substrate disc of diameter 2 cm using a hydraulic dry presser for 2 minutes. About 0.065 g of pulverised EAF Slag (OneSteel Ltd., Sydney, Australia) was placed on top of the carbonaceous substrate as shown in Fig. 8. Alumina powder was then filled and compacted into the cavity of a graphite specimen holder, which was ready to receive the carbonaceous substrate-slag assembly. As a step towards minimising any reactions that could occur at lower temperatures and possibly influence the phenomena to be studied at the temperature of interest, the carbonaceous substrate-slag

assembly was held in the cold zone of the furnace until the desired reaction temperature of 1550 °C was attained. Further on, the insertion into the hot zone followed. A high-resolution charge-coupled device (CCD) camera equipped with an IRIS TV zoom lens was used to capture the live *in-situ* phenomena in the furnace. The beginning of contact time was designed to coincide with the melting of slag. The output from the camera was channelled to a TV monitor and a digital video disc recorder (DVD) to record the entire process as a function of time. This feature allows specific images, which display the contact between the slag and carbonaceous material, to be captured as a function of time from the DVD into the computer. The system was also equipped with a time-date generator to display the duration of each experimental run that lasted up to 30 minutes.



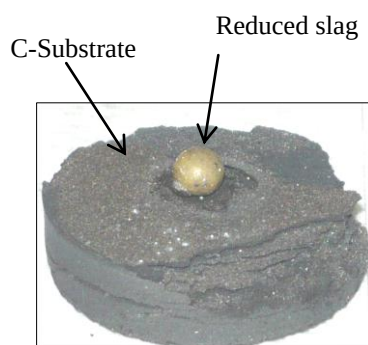
**Fig. 8 Pulverised Slag Placed at the Central Position of Carbonaceous Substrate.**

## 3 Results and Discussion

### 3.1 Slag-Substrate System after Reaction

Fig. 9 shows the slag-substrate system after the slag-foaming process.

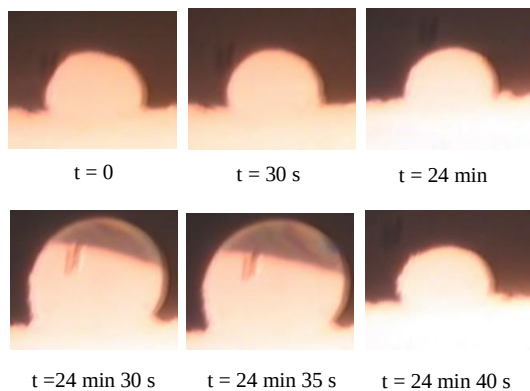
The reduced slag is spherical, indicating that it solidified from the molten state at the experimental temperature of 1550 °C.



**Fig. 9 Slag-Substrate System after Slag Foaming**

### 3.2 Preliminary Snapshot Demonstration.

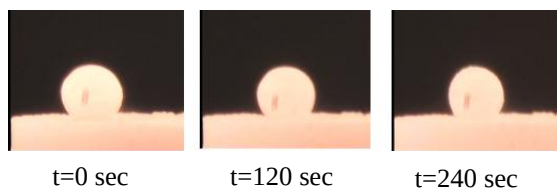
Fig. 10 demonstrates the shape of a reacting molten slag during the first 25 min of slag-carbon interaction at 1550 °C. The size of the slag, and consequently its volume, varies as the reaction time changes. However, visual observation reveals that there is no specific trend in the variation of bubble size with time and, for coke-polymer blends, the first few minutes of slag-carbon interaction is critical to the overall foaming process. Accordingly, although the total reaction time for each experiment was 40 min, attention was concentrated on the first 4 mins after the carbon-slag assembly has been pushed into the hot reaction zone of the furnace. Variation of contact angles with time and also as function of carbonaceous blend was not considered in this investigation, as this was thoroughly treated in a previous research (Blagus *et al.*, 2013). Emphasis was placed on variation of the ratio of volume at time  $t$  to the initial volume, as function of time for each carbonaceous blend.



**Fig. 10 Snapshots Showing the Initiation, Progress and Termination of the Slag Foaming Process.**

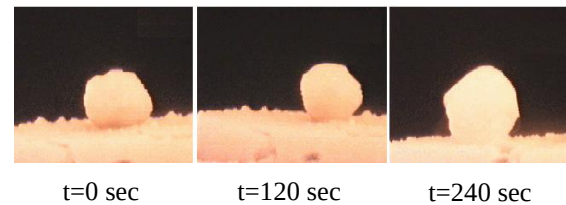
### 3.3 Snapshots of Foaming Slag as Function of Time for each Blend

Fig. 11 shows snapshots of the foaming slag at 0, 120 and 240 s, when the carbonaceous substrate consisted of only coke. No noticeable change in the size of the bubble is observed in the first 4 min, suggesting lack of foaming activity, when coke alone is used as the carbonaceous substrate.



**Fig. 11 Slag Foaming as a Function of Time for Metallurgical Coke.**

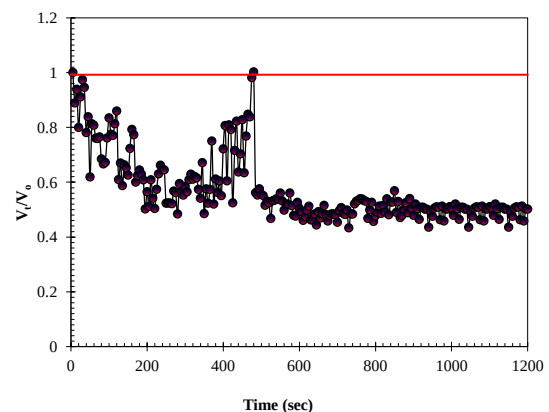
The snapshots of the foaming slag in the same period are illustrated for the carbonaceous substrate with 30 wt % ELT addition. The size of the bubble at  $t = 240$  s is significantly larger than at  $t = 0$  and  $t = 120$  s, suggesting vigorous carbon-slag interaction. At this stage it is apparent that addition of ELT to coke has an influence on carbon-slag reactivity. However, this is based on visual observation only. Detailed quantitative treatment of variation in size and volume is discussed in Section 3.4.



**Fig. 12 Slag Foaming as a Function of Time for 70% Coke-30% ELT.**

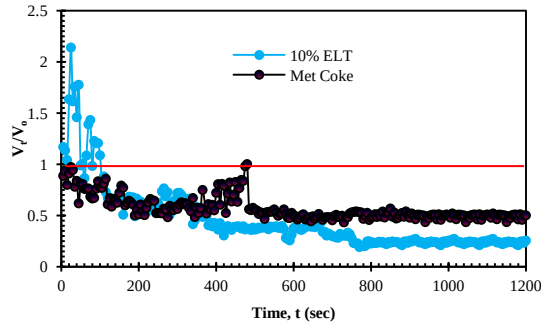
### 3.4 Results of $V_t/V_0$ Measurements

Since  $V_0$  is the initial volume of the slag droplet immediately after complete melting of the slag, values of  $V_t > V_0$  or  $V_t/V_0 > 1$  imply active carbon-slag reactivity. The results of the plots of  $V_t/V_0$  against time are illustrated in Figs 13-17. From Fig. 13, a greater section of the plot of  $V_t/V_0$  against  $t$  is almost essentially below 1, suggesting slow carbon-slag interaction and low slag foamability.



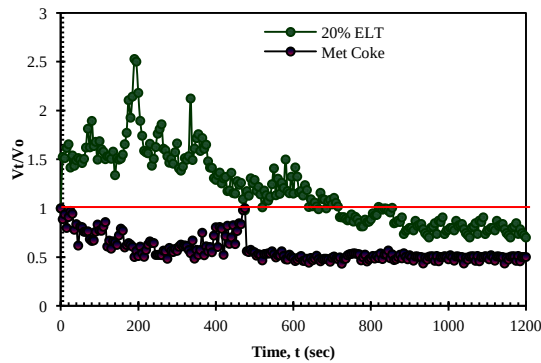
**Fig. 13  $V_t/V_0$  as a Function of Time for 100% Met Coke.**

Fig. 14 combines the plot of coke alone with that of 10% ELT blending. Improvement in slag-carbon interaction is apparent in the first 100 s followed by a period of inactivity.

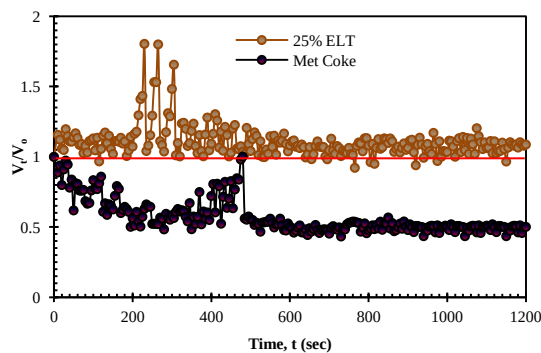


**Fig. 14 Effect of Replacing 10% of Met Coke with ELT.**

Foaming is still better for the blend up to about 300 s, beyond which slag-carbon interaction for the blend falls below that of the coke. The combined plots of  $V_t/V_o$  for coke and 20% ELT blending are shown in Fig. 15. Significant improvement in foaming is observed evident by the plot of the blend being above that of coke in the entire duration of the process. The plot for 25% ELT replacement is not very different from what is observed for 20% ELT replacement, except that foamability is slightly lower than for 20% ELT but predominantly above that of coke.

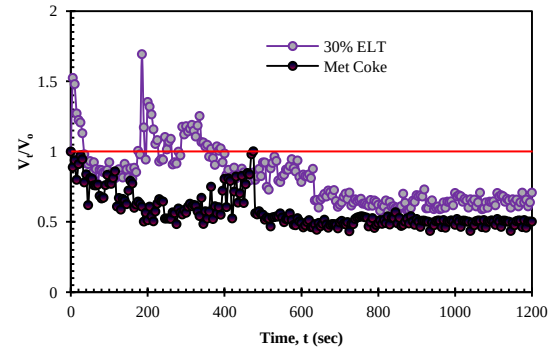


**Fig. 15 Effect of Replacing 20% of Met Coke with ELT.**



**Fig. 16 Effect of Replacing 25% of Met Coke with ELT.**

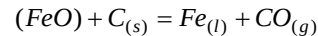
The plot for the final replacement (30% ELT blending) is shown in Fig. 17, along with that of coke for comparison.



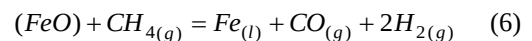
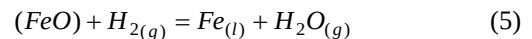
**Fig. 17 Effect of Replacing 30% of Met Coke with ELT.**

Foamability declines in comparison with those of 20% and 25% ELT but practically above that of coke in the entire region of the graph.

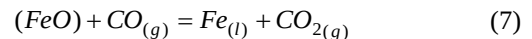
At this stage it is clear that blending of coke with ELT results in improved foamability. Foaming is a function of the rate of gas generation and the level of retention of the gas. Equation (1) is recalled below to assist in the discussion of the gas produced from the slag-carbon interaction.



Evidence from the work done by Sahajwalla *et al.*, (2009) indicates that remnants of the polymer are retained in the carbonaceous blend after treatment in the drop-tube furnace. These can contribute to the reduction of the slag in the form of volatiles in reaction Equations (5) and (6).



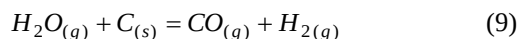
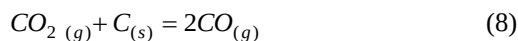
The major gas expected from the slag-carbon interactions is CO, which can give an indication of the extent of slag foaming. Some CO<sub>2</sub> is also expected from the reduction of FeO by emitted CO, as indicated in Equation (7).



### 3.5 Gas Emission Studies

The concentrations of CO and CO<sub>2</sub> in the off-gas as measured continuously by the IR gas analyser are discussed in this section. For all the carbonaceous substrates utilised for this investigation, gas emission commenced immediately after insertion of the slag-carbon assembly in the hot reaction zone of the furnace and it is apparent from the plots in Figs 18-22 that the concentration of CO in the off gas is higher than that of CO<sub>2</sub> as discussed under Section 3.4. Further, as was observed by Dankwah *et al.* (2011), CO concentration is expected to be higher than that of CO<sub>2</sub> owing to a

dominant Boudouard and water gas reactions, illustrated in Equations 8 and 9, respectively.



Maximum CO gas emissions attained were 3.7708, 3.8734, 4.4347, 4.1748 and 4.5549 vol% for coke, 10% ELT, 20%ELT, 25% ELT and 30% ELT, respectively.

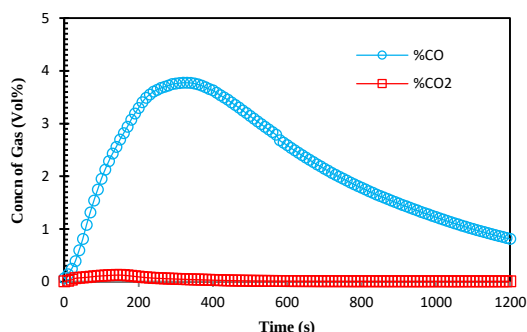


Fig. 18 Gas Emission Behaviour by Met Coke.

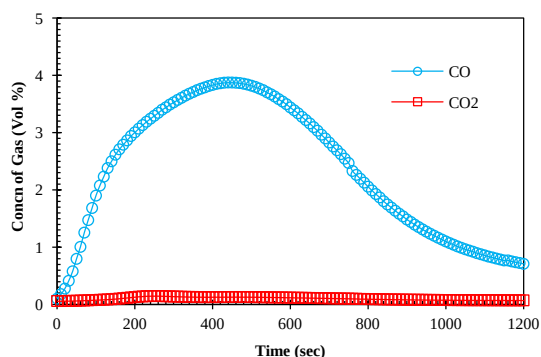


Fig. 19 Effect of Replacing 10% of Met Coke with ELT on Gas Emission Behaviour.

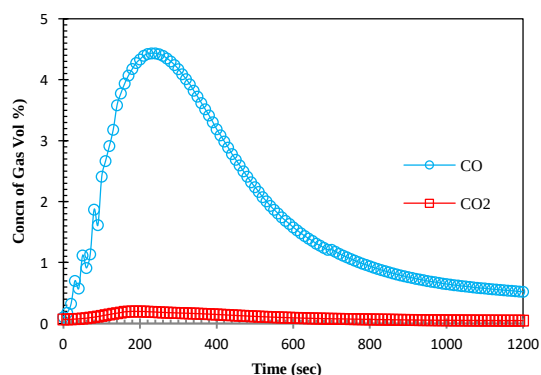


Fig. 20 Effect of Replacing 20% of Met Coke with ELT on Gas Emission Behaviour.

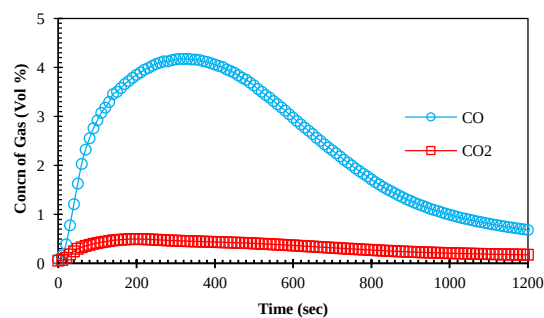


Fig. 21 Effect of Replacing 25% of Met Coke with ELT on Gas Emission Behaviour.

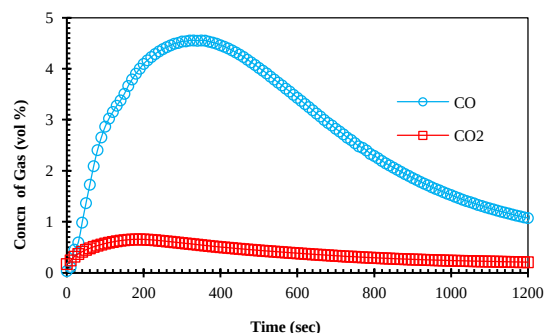


Fig. 22 Effect of Replacing 30% of Met Coke with ELT on Gas Emission Behaviour

### 3.6 Maximum Rates of Reaction

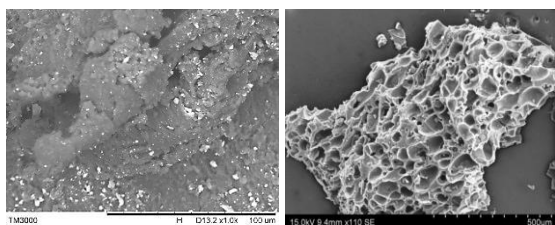
Maximum rates of reaction per area of reaction surface were calculated for each carbonaceous reductant. The results are presented in Table 6. From Table 6, the maximum rate of reaction increases with the proportion of ELT blended with coke.

Table 6 Maximum Rate of Reactions for Each Carbonaceous Reductant.

| Reductant | Maximum Rate of Reaction<br>( $\mu\text{mol cm}^{-2} \text{s}^{-1}$ ) |
|-----------|-----------------------------------------------------------------------|
| Met Coke  | 15.8                                                                  |
| 10%ELT    | 17.1                                                                  |
| 20%ELT    | 20.3                                                                  |
| 25%ELT    | 21.7                                                                  |
| 30%ELT    | 24.5                                                                  |

Work done by Zaharia *et al.*, (2009) showed that remnants of the ELT are retained in the coke-ELT mixture after treatment in the drop-tube furnace. This could subsequently contribute to gas emissions from the carbonaceous substrate and, consequently, the reduction and foaming processes. Charring of the polymer is accompanied by emission of gaseous species that may result in a more porous carbonaceous substrate as illustrated by the SEM in Fig. 23 for raw ELT (Fig. 23 a) and charred ELT (Fig. 23b).





**Fig. 23 SEM Photomicrographs of a) Raw ELT and b) Charred ELT (Farzana, 2016).**

The observed improved porosity in charring or treatment in the DTF is carried over to the coke-ELT blends, as observed by Zaharia *et al.*, (2012). Improvement in the porosity of the carbonaceous substrate is accompanied by improved slag-carbon interaction.

## 4 Conclusions

The effect of ELT addition on slag foaming in EAF steelmaking has been investigated using the sessile drop approach in a laboratory scale horizontal tube furnace. Measured values of  $V_f/V_o$  as a function of time indicate that ELT addition is beneficial to slag foaming. The billions of ELTs currently held in various stockpiles across the globe can be diverted for use as source of carbon for slag foaming in EAF steelmaking.

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## References

- Ameling, D., Petry, J., Sittard, M., Ullrich, W. and Wolf, J. (1986), "Studies of Foamed Slag Formation in the Electric Arc Furnace", *Stahl und Eisen*, Vol. 106, No.11, pp. 625-630.
- Arion, A., Baronnet, F., Lartiges, S. and Birat, J. P. (2001), "Characterisation of Emissions during the Heating of Tyre Contaminated Scrap", *Chemosphere*, Vol. 42, No. 5-7, pp. 853-859.
- Atal, A. and Levendis, Y. A. (1995), "Comparison of the Combustion Behaviour of Pulverized Waste Tyres and Coal". *Fuel*, Vol. 74, No. 11, pp. 1570-1581.
- Berruoco, C., Esperanza, E., Mastral, F. J., Ceamanos, J., and Garcia-Bacaicoa, P. (2005), "Pyrolysis of Waste Tyres in an Atmospheric Static-bed Batch Reactor: Analysis of the Gases obtained". *J. Anal. Appl. Pyrolysis*, Vol. 73, pp. 65-73.
- Blagus, A. V., Dankwah, J. R. and Sahajwalla, V. H. (2013), "Interfacial Reactions between Coke/HDPE Blends and High Carbon Ferromanganese Slag", *ISIJ International*, Vol. 53, No. 1, pp. 41-47.
- Chang, Y. -M. (1996), "Tyre Degradation Rate and Product Yields". *Resources, Conservation and Recycling*, Vol. 17, No. 2, pp. 125-139.
- Chen, J. H., Chen, K. S. and Tong, L. Y. (2001), "On the Pyrolysis Kinetics of Scrap Automotive Tyres". *Journal of Hazardous Materials*, Vol. 84, pp. 43-55.
- Clauzade, C. (2006), *End-of-life Tyres in Electric Arc Furnaces: An Industrial Success Story*, Technical Report by Aliapur, Lyon, France, 8 pp.
- Corbari, R., Matsuura, H., Halder, S., Walker, M., Fruehan, R. J. (2009), "Foaming and the Rate of the Carbon-Iron Oxide Reaction in Slag", *Metallurgical and Materials Transactions B*. Vol. 40, No. 6, pp. 940-948.
- Cunliffe, A. M. and Williams, P. T. (1998), "Composition of Oils derived from the Batch Pyrolysis of Tyres". *Journal of Analytical and Applied Pyrolysis*, Vol. 44, No. 2, pp. 131-152.
- Dankwah, J. R. and Koshy, P. (2013), "Production of Metallic Iron from Iron Oxide ( $Fe_2O_3$ ) using End-of-life Rubber Tyre and its Blends with Metallurgical Coke as Reductants", *International Journal of Engineering Research in Africa*, Vol. 10, pp. 1-12.
- Dankwah, J. R., Koshy, P., O'Kane, P. and Sahajwalla, V. (2012), "Reduction of FeO in EAF Steelmaking Slag by Blends of Metallurgical Coke and End-of-life Tyres", *Steel Res. Int.*, Vol. 83, No. 8, pp. 766-774.
- Dankwah, J. R., Koshy, P., Saha-Chaudhury, N. M., O'Kane, P., Skidmore, C., Knights, D. and Sahajwalla, V. (2011), "Reduction of FeO in EAF Steelmaking Slag by Blends of Metallurgical Coke and Waste Plastics", *ISIJ Int.*, Vol. 51, No. 3, pp. 498-507.
- Farzana, R. (2016), "Transforming Automotive Waste into Value-Added Materials", PhD Thesis, University of New South Wales, Australia.
- González, J. F., Encinar, J. M., Canito, J. L. and Rodríguez, J. J. (2001), "Pyrolysis of Automobile Tyre Waste. Influence of Operating Variables and Kinetics Study", *Journal of Analytical and Applied Pyrolysis*, Vol. 58, pp. 667-68.
- Ito, K., Fruehan and R. J. (1989), "Study on the Foaming of  $CaO-SiO_2-FeO$  Slags: Part I. Foaming Parameters and Experimental Results", *Metallurgical Transactions B.*, Vol. 20, No. 4, pp. 509-514.
- Juma, M., Korenová, Z., Markoš, J., Annus, J. and Jelemenský, L. (2006), "Pyrolysis and Combustion of Rubber Tyre", *Petroleum and Coal*, Vol. 48, No. 1, pp. 15-26.

- Kongkarat, S., Khanna, R., Koshy, P., O’Kane, P., Sahajwalla, V. (2012), “Recycling Waste Polymers in EAF Steelmaking: Influence of Polymer Composition on Carbon/slag Interactions”, *ISIJ International*, Vol. 52, pp. 385 – 393.
- Lanoir, D., Trouvé, G. & Delfosse, L. (1997), “Physical and Chemical Characterization of Automotive Shredder Residues”, *Waste Management*, Vol. 17, No. 8, pp. 475-482.
- Laresgoiti, M. F., Caballero, B. M., De Marco, I., Torres, A., Cabrero, M. A. and Chomón, M. J. (2004), “Characterization of the Liquid Products obtained in Tyre Pyrolysis”, *Journal of Analytical and Applied Pyrolysis*, Vol. 71, No. 2, pp. 917-934.
- Lee, J. M., Lee, J. S., Kim, J. R. and Kim, S. D. (1995), “Pyrolysis of Waste Tyres with Partial Oxidation in a Fluidized-bed Reactor”, *Energy*, Vol. 20, No. 10, pp. 969-976.
- Lotun, D. and Pilon, L. (2005). “Physical Modeling of Slag Foaming for Various Operating Conditions and Slag Compositions”. *ISIJ International*, Vol. 45, No. 6, pp. 835-840.
- Orr, E. C., Burghard, J. A., Tuntawiroon, W., Anderson, L. L. and Eyring, E. M. (1996), “Co-processing Waste Rubber Tire Material and Coal”, *Fuel Processing Technology*, Vol. 47, No. 3, pp. 245-259.
- Rahman, M., Khanna, R., Sahajwalla, V. and O’Kane, P. (2009), “The Influence of Ash Impurities on Interfacial Reactions between Carbonaceous Materials and EAF Slag at 1550 °C”, *ISIJ International*, Vol. 49, pp. 329 – 336.
- Rodriguez, I. d. M., Laresgoiti, M. F., Cabrero, M. A., Torres, A., Chomón, M. J. and Caballero, B. (2001). “Pyrolysis of Scrap Tyres”. *Fuel Processing Technology*, Vol. 72, pp. 9-22.
- Roy, C., Darmstadt, H., Benallal, B. and Amen-Chen, C. (1997). “Characterization of Naphtha and Carbon Black obtained by Vacuum Pyrolysis of Polyisoprene Rubber”, *Fuel Process. Technol.*, Vol. 50, pp. 87–103.
- Sahajwalla, V., Rahman, M., Khanna, R., Saha-Chaudhury, N. S., O’Kane, P., Skidmore, C. and Knights, D., (2009), “Recycling Waste Plastics in EAF Steelmaking: Carbon/slag Interactions of HDPE-coke Blends”, *Steel Research International*, Vol. 80, pp. 535 – 543.
- Senneca, O., Salatino, P. and Chirone, R. (1999), “A Fast Heating-rate Thermogravimetric Study of the Pyrolysis of Scrap Tyres”. *Fuel*, Vol. 78, pp. 1575-1581.
- Williams, P. T. and Bottrill, R. P. (1995), “Sulfur-polycyclic Aromatic-hydrocarbons in Tyre Pyrolysis oil”, *Fuel*, Vol. 74, No. 5, pp. 736-742.
- Zaharia, M., Sahajwalla, V., Saha-Chaudhury, N., O’Kane, P., Fontana, A., Skidmore, C. & Knights, D. (2012), Recycling of rubber tyres in electric arc furnace steelmaking: Carbon/slag

reactions of coke/rubber blends, *High Temp. Mater. Proc.*, 31(4-5), 593–602.

- Zaharia, M., Sahajwalla, V., Khanna, R., Koshy, P., O’Kane, P., (2009), “Carbon/slag Interactions between Coke/rubber Blends and EAF Slag at 1550 °C”, *ISIJ International*, Vol. 49, pp. 1513 – 1521.

## Author



**James Ransford Dankwah** is an Associate Professor of Metallurgical and Materials Engineering at the University of Mines and Technology (UMaT), Tarkwa, Ghana. He holds BSc (Hons), MSc and PhD degrees in Minerals Engineering from the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana, Norwegian University of Science and Technology (NTNU), Trondheim, Norway and University of New South Wales, Sydney, Australia. His research interest is in the areas of Ferrous Metallurgy, High Temperature Metallurgical Processes, Electrometallurgy, Solid Waste Management, Polymer Science and Engineering, Iron and Steelmaking, Corrosion and Corrosion Control and Ferroalloys. He is a fellow of the West African Institute of Mining, Metallurgy and Petroleum (WAIMM).