

DEVELOPING EQUATIONS FOR ESTIMATING CORROSION OF DUCTILE IRON AND CARBON STEEL PIPELINES

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Abstract

The distribution system's efficacy and reliability are greatly affected by the water quality in the pipelines. It is common practice to measure water's scaling or corrosive potential using the Langelier Saturation Index (LSI). The most common issues with drinking water facilities caused by corrosion and scaling include water loss, reduced facility life, pipe punctures, pipe clogging, and pressure loss in distribution systems. This paper aims to develop equations for calculating the pipe mass loss due to pipe corrosion that is subjected to water characteristics of PH, alkalinity, calcium hardness, TDS, and temperature, which give negative LSI indicators. Ten identical samples, five ductile iron sheets and five carbon steel sheets with dimensions of 5 x 3 x 2 cm were subjected to water with LSI indicator values of -0.2, -0.5, -1, -3, and -5. The sheet mass loss was recorded every seven days. Two equations for the two used pipe material types were developed to calculate the mass loss for any LSI indicator value at a given time. It was found that the mass loss due to pipe corrosion for ductile iron pipes was less than that of the carbon steel pipes.

Keywords: Pipe Mass Loss, Langelier Saturation Index, Pipe Corrosion, Scaling, and Drinking Water.

1. INTRODUCTION

One of the major concerns facing the drinking water industry is corrosion, which can have an impact on the cost and quality of drinking water as well as public health [1]. The International Standard Organization (ISO) defines corrosion as the result of a metallic material's physicochemical interaction with its surroundings, which modifies the material's properties [2]. Various physical, chemical, and electrical conditions, including elevated carbon dioxide levels, alkalinity, temperature, and pH, might impact the rate of corrosion [23].

Currently, the drinking water industry faces substantial yearly expenses to manage and prevent corrosion [3].

Corrosion is a destructive process that results in a host of issues, including blocked pipes, shortened facility lifespans, water loss, land subsidence, and pipe punctures. In addition, it causes damage to transmission pipes, pumping equipment, main lines, and domestic plumbing systems [2, 4]. In addition to financial losses, certain heavy metals can infiltrate drinking water and induce pipe corrosion [24].

Lead, cadmium, iron, zinc, copper, and manganese are among the metals mentioned. Lead and cadmium are toxic elements, while iron, zinc, copper, and manganese contribute to aesthetic problems in drinking water, such as changes in taste, color, odor, and the formation of stains in bathrooms. Therefore, the acceptable threshold for each of these metals in drinking water has been determined [5-7]. The annual expenses attributed

to corrosion and scaling in the United States exceed 300 billion dollars or almost 4.5 per cent of the nation's gross national product [8].

Precise data on the extent of corrosion and scale damage in Iran is lacking. However, an analysis of urban wastewater losses reveals that about 31% of the water delivered each year is wasted due to the deterioration induced by corrosion in water transmission and distribution pipes. This loss is in addition to the expenses incurred for the replacement and repair of damaged pipes [9]. Scaling and corrosion can both cause harm to the pipes in drinking water systems. Scaling is the result of the interaction of divalent cations of magnesium and calcium with other soluble compounds, leading to the creation of a solid layer on the inner surface of the pipe [10, 11]. Calcium carbonate is a prominent mineral found in the water and is believed to be the main contributor to sediment formation [12, 13].

Precipitation of calcium carbonate in water is a widely used technique for managing scale in drinking water systems. When pipes contain water with an excess of calcium carbonate and have high hardness values, scale development can occur. This can result in pipe blockages and various issues within the household systems, such as higher energy consumption [12, 13]. The occurrence of corrosion or scaling in pipes is influenced by the quality of urban supply sources and the adjustment of these two issues. Additionally, addressing these concerns can lead to improvements in the quality and quantity of drinking water, as well as potential cost reductions [2].

Corrosion control and scaling evaluation are the primary design considerations for engineers due to the significant financial burden of replacing corroded infrastructure such as pipelines, valves, tanks, meters, and connections, which cost millions of dollars per year [3]. The main responsibilities in drinking water treatment plants involve the application of paint and suitable coatings to water transmission and distribution facilities, the implementation of cathodic protection for metal structures, and the maintenance of continuous water flow in transmission and distribution pipes [14]. Alcohol usage is not classified as corrosive according to international rules, such as the EPA [15]. Corrosion indices are indirect techniques employed to assess and diagnose corrosion and scale by examining the properties of water. The Langelier Saturation Index (LSI) and Ryznar Stability Index (RSI) are two instances of such indicators. The accuracy of these indices depends on their capacity to predict the ability of water to experience calcium carbonate precipitation, decomposition, or dissolution, as well as to estimate the degree of undersaturation, saturation, or supersaturation of water concerning calcium carbonate [16], [25], [26].

The calcium carbonate saturation level is displayed by the LSI. It uses pH as a key variable to define the idea of saturation. Stated differently, LSI is the pH shift necessary for water to attain equilibrium [17]. A quantitative relationship between scale formation and calcium carbonate saturation is demonstrated by the RSI. Temperature, total soluble solids (TDS), bicarbonate and calcium ion concentrations, and actual pH all affect the pH value in RSI [18]. The two values demonstrate the difference between the pH at which calcium carbonate reaches saturation and the pH that is seen [19, 20].

The purpose of this paper is to develop equations for each ductile iron and carbon steel pipe based on the LSI indicator. These equations may be used to calculate the mass loss of the pipe material due to corrosion after a certain time for a given LSI indicator value.

2. MATERIALS AND METHODS

The study entails the surveillance of crucial water quality measures, such as pH, alkalinity, calcium content, and temperature.

These parameters are used to calculate the LSI, providing a quantitative measure of the water's potential to be oversaturated or under saturated concerning calcium carbonate. Hydraulic modelling is then employed to simulate the flow conditions within the pipeline. The LSI is integrated into the hydraulic model to assess its influence on friction losses. The methodology aims to quantify the relationship between water quality, LSI, and pipeline losses.

2.1 The Used Materials

Ductile iron is considered one of the most expensive pipes of the piping system for its huge cross sections, weight and volume in addition to its strong performance [27]. On the other hand, carbon steel is considered the most common pipeline metal in the field of piping system industry with its three types of concentration of carbon percentage. Each of the two pipe material types suffers from corrosion and scaling formation which results in pipe material mass loss, Fig. 1.

In this paper, twelve identical samples were used, six of these samples were ductile iron and the other six were carbon steel. For each pipe material type, five samples for to be tested and the sixth for calculating the mass loss ratio, W_{acc}/W_o in which W_{acc} is the accumulated mass loss and W_o is the original sample mass. The dimension of each sample was 10 x 5 x 2 cm, with an average mass of 698.33 and 710 gm for ductile iron and carbon steel respectively, Fig. 2. A sensitive digital scale was used for detecting the sample mass for each time interval, with accuracy of 0.01 mg.

2.2 Water Samples

The study involves monitoring important parameters of water quality, including pH, alkalinity, calcium concentration, and temperature.



Figure 1: Mass loss due to pipe corrosion

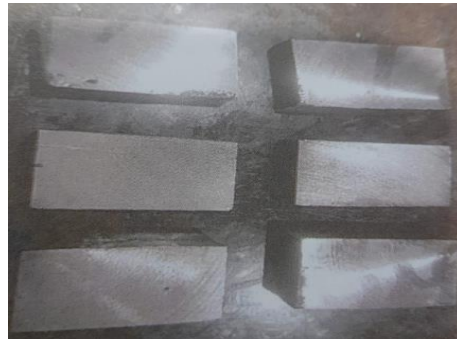


Figure 2: Pipe samples

The acidity levels were measured using a pH meter, the temperature was measured using a thermometer from HM Digital, USA, and the total dissolved solids were measured using a TDS meter at the sampling location. Furthermore, the conventional procedures were used to measure the parameters of total alkalinity, total hardness, concentrations of carbonate anions, and concentrations of calcium cations. The parameter of total dissolved solids was measured at the desired site using portable equipment, and in the laboratory by estimating the remaining dry weight after evaporation. It is important to mention this. The average of three values of these parameters was recorded.

The most commonly used index is the LSI indicator, which was calculated as follows;

$$\text{LSI} = \text{pH} - \text{pHs} \quad (1)$$

$$\text{pHs} = (9.3 + A + B) - (C+D) \quad (2)$$

$$A = (\text{Log} [\text{TDS}] - 1)/10 \quad (3)$$

$$B = -13.12 \times \text{Log} (^\circ\text{C} + 273) + 34.55 \quad (4)$$

$$C = \text{Log} [\text{Ca}^{2+} \text{ as CaCO}_3] - 0.4 \quad (5)$$

$$D = \text{Log} [\text{Alkalinity as CaCO}_3] \quad (6)$$

The variable "pHs" represents the pH value of water that is fully saturated with calcium carbonate. A indicates the concentration of total dissolved solids in milligrams per litre (mg/L). B corresponds to the temperature in degrees Celsius (oC). C represents the calcium hardness in milligrams per litre as calcium carbonate (mg/L as CaCO₃). D represents the total alkalinity in milligrams per litre as calcium carbonate (mg/L as CaCO₃).

The LSI criteria, which provide an assessment of water status, were compiled by [21] and shown in Table 1.

Table 1: LSI criteria with the interpretation of the water status

LSI criteria	Interpretation
LSI > 0	Water is oversaturated and scales.
LSI = 0	Saturated water does not scale.
LSI < 0	Unsaturated water corrodes.

The values of pH range from 3.9 to 8.5 to get higher accuracy to assess the effect of pH on LSI value in the deteriorations of pipe samples. In this paper, only the negative values of the LSI indicator were considered to be in the corrosion zone with values of -0.2, -0.5, -1, -3, and -5, Table 2.

Table 2: Interpretation of Langelier index

Water sample	pH	Calcium mg/l	ALK. mg/l	TDS mg/l	Temp. °c	LSI	pHs	Corrosion case
1	8.5	14	63	500	25	-0.2	8.7	Low corrosion
2	8.1	14	63	125	25	-0.5	8.6	Mild corrosion
3	7.6	14	63	125	25	-1	8.6	Mild corrosion
4	6.1	14	63	550	25	-3	9.1	Severe corrosion
5	3.9	14	63	26	25	-5	8.9	Very severe corrosion

2.3 Methodology and Procedures

As shown in Fig. 3, two rectangular water basins with dimensions of 75 x 25 x 15 cm were constructed from transparent glass with a 5 mm thickness. The pipe sample was placed in each of the five 25 x 25 x 15 cm sections that made up each basin. It was assumed that pH would remain constant for all of the experiments. The sample's five faces that were directly exposed to water showed uniform corrosion, while the bottom face showed no corrosion.



Figure 3: Water basins and its sections

The mass loss by corrosion was assumed to be uniform over the exposed area and was calculated per unit of this area. The experimental procedures were as follows;

1. The ten pipe samples were put in the ten sections of the basin five samples from ductile iron and the other five from carbon steel after recording their original mass.
2. Water five samples, Table 2, were adjusted by checking its components to the target LSI indicator value.
3. Each two basin sections contained water with the same LSI and different pipe samples.
4. For each sample, the mass losses were recorded every seven days and divided by the area of the sample's five faces to obtain the mass losses per unit exposed area.

5. Then, the accumulated mass loss ratios, W_{acc}/W_o were calculated, in which W_{acc} was the accumulated mass loss per unit area, and W_o was the original pipe sample mass per unit in the same area as;

$$W_{acc} = (W_o - \text{the pipe sample mass every 7 days})/110 \text{ cm}^2$$

3. RESULTS AND DISCUSSION

The water chemistry characteristics for each sample were measured and documented. The average concentration of total dissolved solids in various water samples ranged from 26 to 550 mg/L.

The mean values of water acidity and pH in different water samples ranged between 3.9 and 8.5. The mean values of alkalinity and calcium in different water samples were constant values of 63 and 14 mg/l respectively. The water temperature was 25°C. These water parameters gave negative LSI indicator values which resulted in pipe corrosion.

3.1 Corrosion of Ductile Iron and Carbon Steel

Each ductile iron and carbon steel samples were put in the basin sections, with five samples for each type. Then the five water samples with LSI indicator values of -0.2, -0.5, -1, -3, and -5 were added into the sections, where water with the same LSI was added to the different material type. It was realized that in the pipe samples exposed to water with LSI indicator values of -0.2, -0.5, -1, and -3, red sediment layer was formed on it after 18 – 24 hours, which affected the water color, Fig. 4. Also, it was realized that there was the difference between the color of the red layer on both of the ductile iron and the carbon steel samples, this color became black layer for low pH value of -5, as shown in Fig. 5. The red and on the ductile iron was more than that on the carbon steel, which means that the ductile samples have more degradation, see Fig. 6. For instance, for LSI of -5 and time of 42 days, the accumulated pipe mass losses ratio, W_{acc}/W_o was found to be 0.277 and 0.226 for ductile iron and carbon steel pipe samples respectively, which means that W_{acc}/W_o for ductile iron increases by 22.5% than that for carbon steel. The mass losses of the pipe samples had a small rate in the first seven days and it increased gradually with time.

3.2 Equations for Calculating of the Accumulated Mass Ratios:

The corrosion or scaling of drinking water is influenced by various characteristics including pH, temperature, calcium hardness, alkalinity, and TDS. Variations in the values of these elements can alter the stability of the water [22]. The findings revealed that the low LSI water value indicated a significantly higher corrosion rate compared to the high LSI values.

It was found that the accumulated pipe mass losses ratio, W_{acc}/W_o has a directly proportional relationship with the time and an inversely proportional relationship with the LSI indicator values, as shown in Figs (7 and 8).



Figure 4: Red sedimentation on the pipe samples



Figure 5: Red sedimentation layer for LSI values of -0.5, -0.2, -1, and -3 and black layer for low LSI of -5

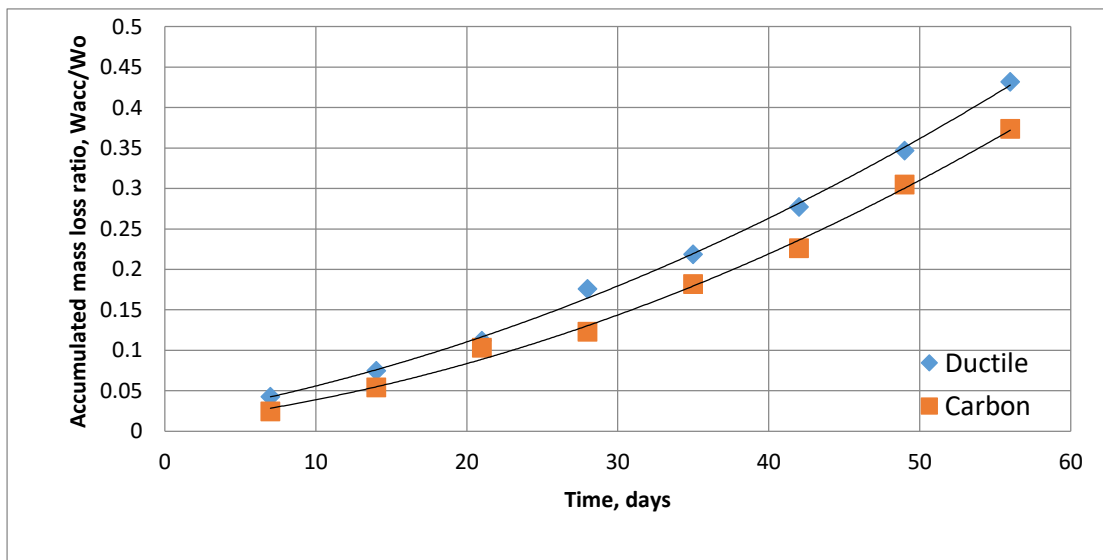


Figure 6: Mass loss ratio at different times for LSI indicator value of -5

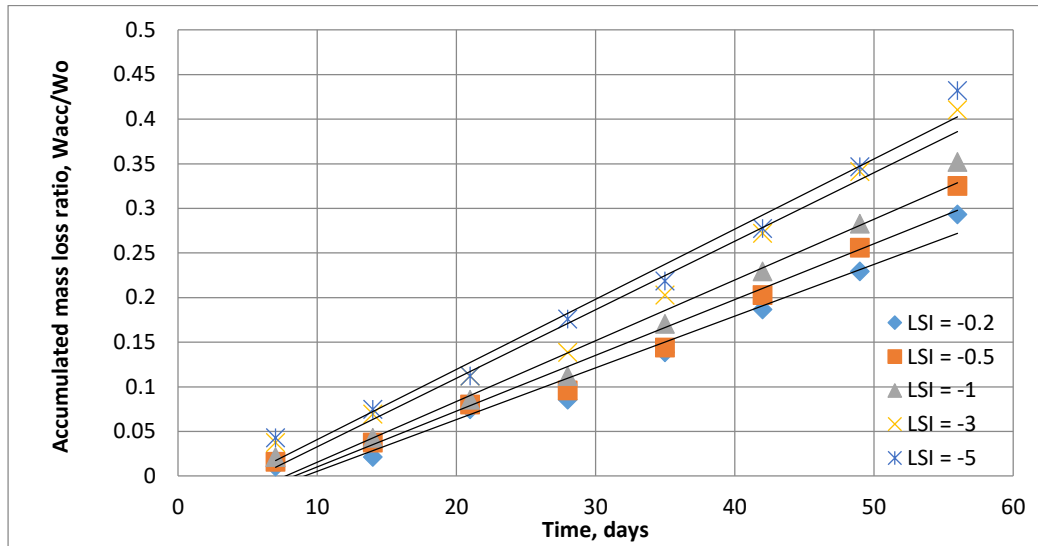


Figure 7: Variation of accumulated mass losses ratio, W_{acc}/W_o for ductile steel samples

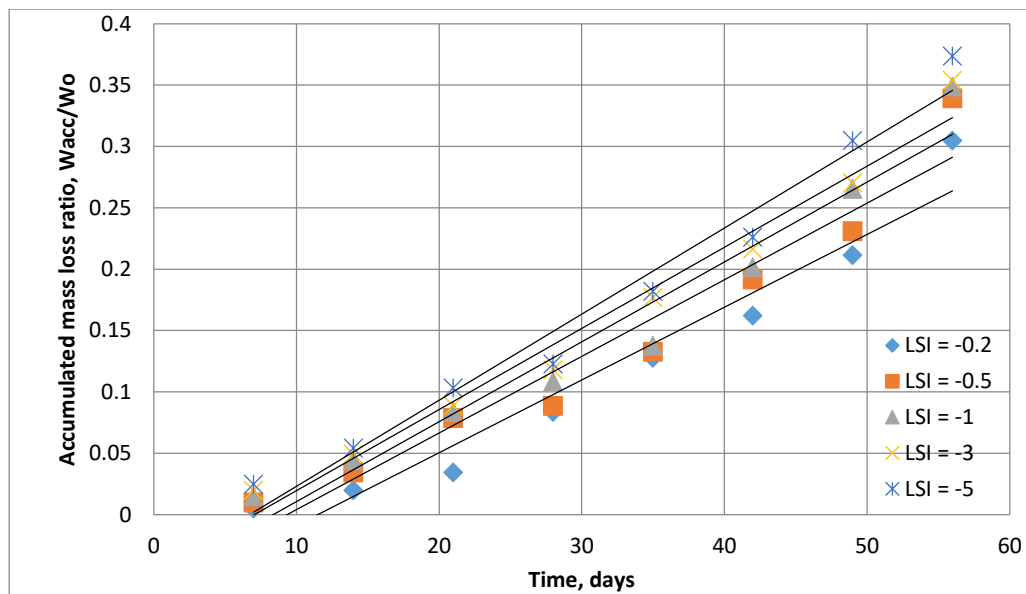


Figure 8: Variation of accumulated mass losses ratio, W_{acc}/W_o for carbon steel samples

The experimental results were examined and used to generate general empirical equations using the regression approach. These equations were then used to estimate the pipe mass losses ratio, W_{acc}/W_o . An analysis was conducted to investigate the relationship between the calculated LSI, time, and the values of W_{acc}/W_o . The established empirical equations can be stated as follows:

For ductile iron pipe samples:

$$\frac{W_{acc}}{W_o} = (-0.0001 (LSI)^2 - 0.0011(LSI) + 0.0057)T - 0.0033(LSI) - 0.0542 \quad (8)$$

For carbon steel pipe sample:

$$\frac{W_{acc}}{W_o} = (0.00002 (LSI) + 0.0061)T - 0.0017 (LSI)^2 - 0.0125 (LSI) + 0.0671 \quad (9)$$

Where: T is the time in days. The validity of these two empirical equations was confirmed by comparing the experimentally obtained results with the calculated values for the pipe mass losses ratio, W_{acc}/W_o , of the ductile iron and carbon steel, as depicted in Figures 9 and 10. The results demonstrate a strong correlation between the measured and projected W_{acc}/W_o values.

4. CONCLUSIONS

The purpose of this paper is to develop empirical equations for calculating the pipe material mass losses ratio, W_{acc}/W_o as a function of time and LSI indicator. After analyzing the experimental results the following conclusions were collected;

1. The used LSI indicator values in this paper were negative, to study the pipe material corrosion case.
2. The rate of the pipe material mass losses ratio, W_{acc}/W_o increases with time.
3. The pipe material mass losses ratio, W_{acc}/W_o decreases as the LSI indicator value decreases.
4. Ductile iron degrades faster than carbon steel by about 22.5% for LI indicator value of -5 after time of 42 days.
5. The pipe material mass losses ratio, W_{acc}/W_o may be calculated using the developed empirical equations for ductile iron and carbon steel pipes.

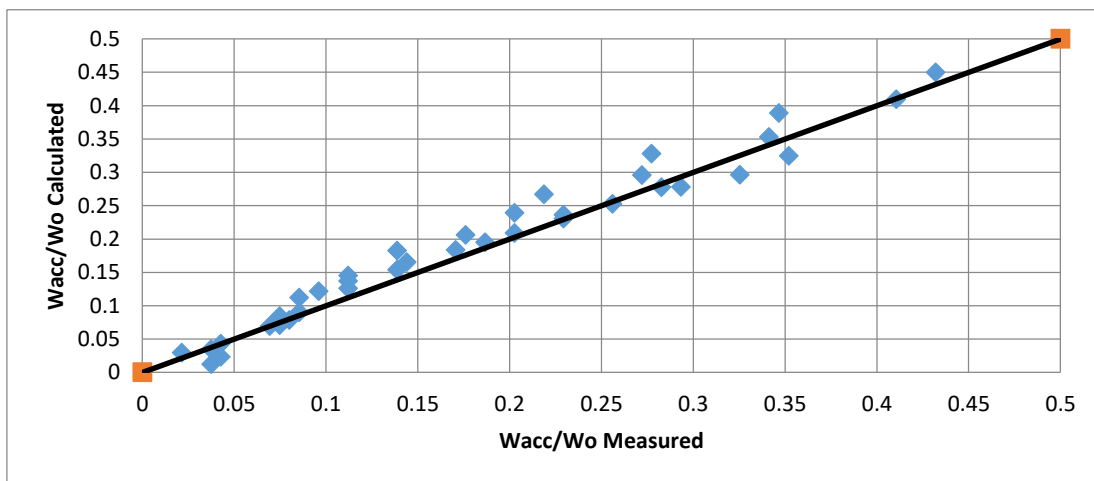


Figure 9: Measured and calculated accumulated mass ratio, W_{acc}/W_o for ductile iron

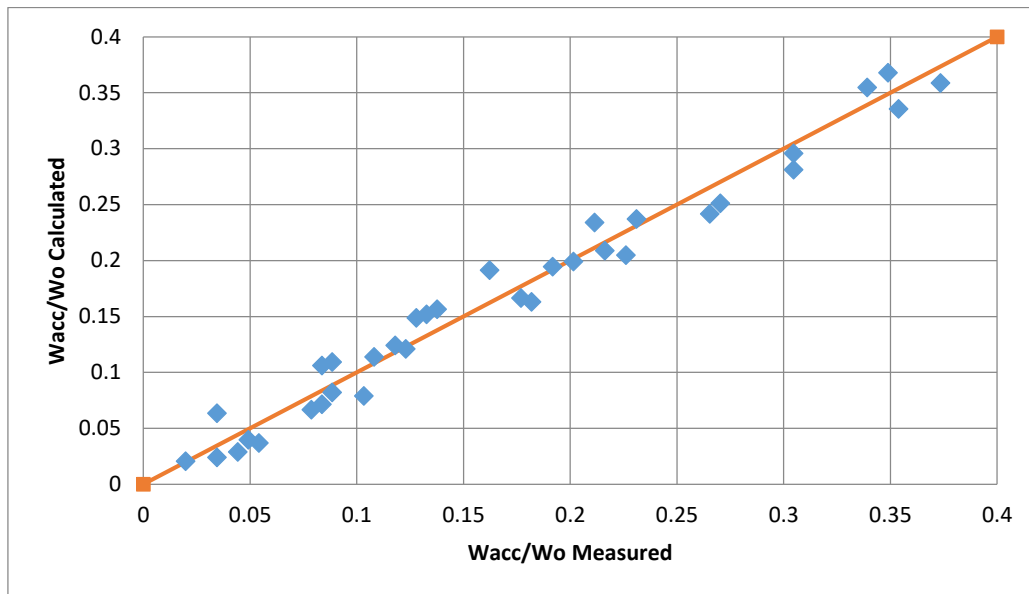


Figure 10: Measured and calculated accumulated mass ratio, Wacc/Wo for carbon steel

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