Corrosion in a sugar mill

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Abstract. Material degradation is a serious problem in the cane industry. The purpose of this paper is to assess the causes and impact of corrosion, abrasion and erosion at the different stages in the production of sugar in a milling plant. Challenges created due to the material degradation problems and solutions to these problems would be discussed. A survey was first performed to observe, visually, the corrosion damage in the milling plant. Electrochemical tests were performed to determine the rate of corrosion of sugar cane juices on commonly used metals in the cane industry, namely mild steel, 3Cr12 steel, 304L stainless steel and 316L stainless steel. Simple immersion test was performed according to ASTM G 31 to compare the corrosivity of conveyor chains. Various types of material degradation were observed in the different stages of sugar production. Abrasion, erosion and/or corrosion were the main ones. From the electrochemical tests, it was observed that the pre-extractor juice had the highest corrosion rate and syrup had the lowest one. This was confirmed by the immersion tests. Hence, several alternative materials were proposed for the various environments in the cane industry.

1. Introduction

Sugar cane was introduced in Mauritius back in 1639. In 1860, sugar production reached 121000 tonnes with 259 factories. Sugar production which reached a peak of 718 000 tonnes in 1973 over some 85 000 hectares [1]. In 2012, the total sugar production amounted to 413000 tonnes [2] and in 2019 it declined to 331,105 tonnes [3]. In 2009, there was a significant decrease (36%) in sugar prices. This led to a centralisation process of the cane milling operations and to a significant valorisation of the co-products of sugar cane.

At the mill, when the cane is received, it is mechanically unloaded, placed in a large pile, for the milling process. Then the sugar cane is shredded. This is performed by a shredder which acts like a hammer and smashes the sugar cane against an anvil in order to slit it. The sugar cane is then crushed through rollers for juice extraction. It should be noted that multiple sets of three-roller mills are most commonly used although some mills consist of four, five, or six rollers in multiple sets. Conveyors are used to transport the crushed cane from one mill to the next. The crushed cane exiting the last mill is called bagasse. Bagasse is burnt in power stations to produce electricity and steam power. Being one of the most efficient photosynthesizers, sugar cane is the plant that can produce among the most biomass per unit surface area.
The collected juice is strained to remove large particles and then processed in a clarifier to remove sludge. It should be noted that cane juice is a complex mixture of organic acids, inorganic salts, suspended soil, and fibre [4]. In the clarifier, the temperature may rise to 95°C. The concentration of the clarified juice is increased through the evaporation process to produce syrup. The syrup thus obtained is clarified by adding lime, phosphoric acid, and a polymer flocculent. It is then aerated and filtered in the clarifier. From the clarifier, the syrup goes to the vacuum pans for crystallization. From the crystallizer, the massecuite is transferred to high-speed centrifugal machines, in which the molasses and sugar crystals are centrifuged. Molasses, obtained as a by-product, is presently distilled into ethanol. This ethanol is utilized for making rum and, in the future, it is expected to be used for powering motor vehicles in replacement of fossil fuel, namely gasoline. The excess is exported. It should be noted that, for exportation, the sugar is stored in a centralized storage and handling unit from where it is loaded into ships.

The main components of sugar cane juice are [5]: glucose(dextrose), fructose (laevulose), sucrose, starch, dextran and gums, organic acids, mineral constituents, protein and microorganisms (bacteria, yeast and fungi). The pH of the different types of juices extracted is shown in Table 1.

<table>
<thead>
<tr>
<th>Types of juices</th>
<th>pH range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-extractor mill juice</td>
<td>4.5-5.5</td>
</tr>
<tr>
<td>Draft juice</td>
<td>6.0-7.0</td>
</tr>
<tr>
<td>Clarified juice</td>
<td>7.0-7.5</td>
</tr>
<tr>
<td>Syrup</td>
<td>6.0-7.2</td>
</tr>
<tr>
<td>Masscuite</td>
<td>6.0-7.0</td>
</tr>
<tr>
<td>Molasses</td>
<td>6.0-7.0</td>
</tr>
</tbody>
</table>

The slightly acidic nature of the sugar cane juices and substantial amount of silica cause much corrosion and abrasion problems in sugar factories. The acidity level of sugar cane juice is mainly due to the presence of some acids, namely: aconitic, citric, malic, oxalic, glycolic mesaonic tartic, succinic and fumaric acid. This is amplified by the use of acids and other corrosive chemicals such as caustic soda. In addition, there are approximately 50 different kinds of microorganisms which raises the acidity of the juice [6]. The presence of the microorganisms leads to the formation of a biofilm which results in microbial influenced corrosion. Erosion problems are also common in the boilers, economisers, air heaters and superheaters. This can lead to worn out and perforated components.

In Indian sugar factories, it has been found that the corrosion cost is as high as USD 250 million, with the following factors being the main cause of corrosion [7]:

- Abrasion, erosion, corrosion wear and galvanic corrosion
- Surface finish
- Vapours and high temperatures
- Acidic Environment and use of chemicals

Problems of corrosion in the cane industry have been reported as early as the 1920s [6]. Corrosion of brass tubes used in juice heaters and evaporators were investigated. Dezinification was observed as the major type of corrosion in these tubes. The reasons varied, based on the sugar milling plants considered, with the acidity of the juice and microbial induced corrosion being the ones observed [8,6]. Corrosion problems in evaporators, juice heaters and boilers have been reported since then. Though the corrosion in evaporators is an old problem, nowadays, different materials are being used, including carbon steel, in their fabrication. However, similar types of problems are still being observed [9].
Crystallisation fouling, sometimes referred to as scaling, is another major issue which occurs in juice heaters, in syrup heaters and in juice evaporators. The corrosion agents, such as silicates, sulfates, phosphates and calcium, are either dissolved or suspended in the process fluid flowing through these equipment [10].

Boilers have also been facing material degradation problems in the cane industry. Considering bagasse fired boilers [11], it has been reported that fireside corrosion of superheater tubes is generally more severe than steam-side corrosion. This is due to the high concentrations of alkali, sulphur and chlorine gases and particles on the fireside. Stainless superheater tubes suffer higher corrosion rates at much lower temperatures in biomass fuelled boilers than in coal-fired boilers. Occurrence of corrosion fatigue has also been observed in boilers in the cane industry. In a study performed in South Africa, corrosion fatigue has been found to be the second most common type of failures in fire tube boilers. It involves the interaction of cyclic loading, corrosive environment and a high residual stress field. Most of the water tube boilers that were found to exhibit corrosion fatigue were in the higher pressure range of around 70 bars or higher [12]. Under such conditions, stress corrosion cracking have also been observed. This problem may be prevented by using appropriate water treatment [12].

Several methods have been used for preventing corrosion in the sugar industry. Carbon steels in sugar plant equipment are gradually being replaced with other alloys or stainless steels [9]. 3Cr12 steel and ferritic stainless steel (type 410L) have replaced carbon steel where better corrosion resistance is required. For juice production and downstream applications, where higher corrosion resistance is required, austenitic stainless steels type 304 or 316 are commonly selected [13]. They also offer the advantage of being easy to shape and weld. Otherwise, coatings are used during maintenance work for corrosion protection of both worn and new equipment, parts, and components. Such coatings include, for example, polymer coatings such as epoxies [14, 15] and thermal arc spraying. They are mainly used for bearings, flanges, pump casings, shredder hammers, conveyor screws and valve covers.

With the cost cutting obligations in the sugar sector in Mauritius, decreasing corrosion cost is one of the priorities of the stakeholders in this sector. Hence, in this paper, the causes and impact of material degradation at the different stages in the production of sugar would be assessed. Challenges to be tackled and solutions to these problems would be discussed. In addition to decreasing corrosion costs in the sugar industry, the results of this study is expected to lead to a decrease in investment costs in future projects.

2. Materials and Methods

Many processes are undertaken during the production of sugar and its co-products. However, this paper looks into the materials degradation problems in the milling plants, the sugar and molasses production processes and in the boiler system. A major sugar mill was considered as a case-study.

The macro corrosion damage in the milling plant under consideration was first observed. Micro corrosion damages, from samples of corroded and damaged parts, were observed using an optical microscope. Feeder tables, slats and chains, shredder and shredder hammers, overhead crane, mill, pumps and pipes were considered for analysis, as they were the mostly impacted parts. Maintenance data were collected. Corrosion rate in the molasses and syrup pipelines and slats were determined by measuring their dimensions after their replacement. Each corroded pipe was cut and the thickness was determined using a micrometre after that they were thoroughly cleaned. The thickness of the pipes was measured along their circumference. Hence the corrosion rate was determined. Each of the slats, have a length of 2 m and their thickness was measured at 8 equal intervals.
Electrochemical tests were performed to determine the rate of corrosion of sugar cane juices on commonly used metals in the sugar industry, namely mild steel, 3Cr12 steel and stainless steel AISI 304L (ss304) and AISI 316L (ss316). The corrosion rate of caustic soda on these metals was also determined, being one of the main chemicals used in sugar industry. The metal samples were cut to a square of side length 20 mm. They were polished using silicon carbide abrasive to a grit size of 600. Tafel tests were performed using the three electrode electrochemical cell arrangement. The polarisation curves were recorded in the range ±1500 mV at a sweep rate of 100 mV min⁻¹. A standard calomel electrode was used as the reference electrode and the auxiliary electrode was made of platinum.

Seamless boiler tubes, DIN 17175 ST 35.8, were found to experience solid particle erosive wear due to the impaction of fly ash particles. This most probably occurred synergistically with corrosion due to the corrodants present in the flue gas stream. Volatile alkali, sulfates and chloride vapours are present in the flue gas which combine with other ash constituents, and condense to form molten deposits. This may cause rapid material damage due to oxidation, sulfidation, chloridation, and even hot corrosion [16,17,18]. The boiler produces superheated steam at a temperature of 490°C and a pressure of 83 bar. To investigate the SPE problem, ST 35.8 together with other commonly used materials in the sugar industry were tested for their erosion resistance using a test rig was designed in accordance to ASTM G76-13 [19]. ST35.8 steel, AISI 1020 steel, ss304 and ss316 were selected for the test. The hardness of the materials and their surface roughness are shown in Table 2. Harder and more brittle materials were not considered as erosion increases with increase in hardness of the material [20]. Austenitic stainless steels ss304 and ss316, on the other hand, have commonly been used as boiler tubes [21,22].

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness (Vickers)</th>
<th>Surface roughness parameter (µm)</th>
<th>roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ra</td>
<td>Rq</td>
<td></td>
</tr>
<tr>
<td>AISI 1020 steel</td>
<td>127</td>
<td>0.15</td>
<td>0.18</td>
</tr>
<tr>
<td>ST35.8 steel</td>
<td>120</td>
<td>0.14</td>
<td>0.17</td>
</tr>
<tr>
<td>ss304</td>
<td>140</td>
<td>0.05</td>
<td>0.07</td>
</tr>
<tr>
<td>ss316</td>
<td>153</td>
<td>0.06</td>
<td>0.09</td>
</tr>
</tbody>
</table>
The equipment used for testing solid particle erosion is shown in Figure 1. It was first calibrated according to ASTM G76, using AISI 1020 steel. Erodent particles used for the calibration was aluminium oxide powder. The particle velocity was set at 30±2 m/s through adjustment of the air pressure to 140 kPa. The particle size was 50µm. The test time was set to 600 s. The angle between the nozzle axis and the specimen surface was adjusted to $90 \pm 2^\circ$. The test temperature was 25°C and the particle feed rate was set at $0.033 \pm 0.008$ g/s. The average erosion value obtained was $3.43 \times 10^{-3} \text{ mm}^3/\text{g}$. Each selected specimen was then subjected to a jet of particles of the fly ash under same conditions for a total duration of 600s. The test results were then analysed by measuring mass loss and erosion values calculated as required in the ASTM G76 standard.

3. Results and discussion

3.1 Types of material degradation

The different types of corrosion observed in the various parts of the sugar factory are described below.

3.1.1 Atmospheric corrosion

The milling factory under consideration is situated 2.5 km from the western coast of Mauritius. The corrosivity of the atmosphere is expected to be in the C3 category [23]. Atmospheric corrosion and galvanic corrosion were observed on every equipment that was exposed outdoors. Equipment which were mostly affected by atmospheric corrosion are the feed tables, cane carrier and the travelling cranes. Parts of other equipment, such as coupling systems, which were present outdoors, were also found to be corroded. Atmospheric corrosion was also observed on other structures present outdoors, as shown in Figure 2.
3.1.2 Abrasion-corrosion and fretting

Fretting was observed on feed tables arising mainly due to the contact surfaces between the table and the chains as shown in Figure 3.

These tables have for function to carry the cane bundles for further processing in the factory. They consist of arrays of slats, with chain systems that drag the cane to the discharge. The tables are fitted with levellers and carding drums to even and compact the cane on the tables prior to shredding. These ensure that the cane falls smoothly off at the discharge end.

Abrasion-corrosion was observed as the sugar cane is dragged along with small debris, such as small rocks, over the feed table. Also, the surfaces of the table rub against the surfaces of the slats and chains leading to a two-body abrasive wear mechanism. Corrosion follows due to the corrosive nature of juice or other liquids, such as water, which may be present on the surface. Fretting wear was observed due to heavy vibrations between the chains and the slat as it drags the bundles of sugar cane in the factory. Fretting was equally observed in the cutter and the shredder hammers due to high friction coupled with bagasse fibres and pre-extractor juice, which is acidic, as shown in Figure 4.

3.1.3 Milling rollers

The rollers consist of machined ridges extending circumferentially around the rollers. The grooves, as shown in Figure 5, are characteristically even spaced along them, which allow the juice to flow out while forcing the cane between the rollers. They were casted from cast iron and mounted on shafts. The high pressure between rollers, the abrasive nature of the
sugar cane fibres and the corrosive nature of the sugar cane juice lead to wearing and frequent breaking of the crest.

The milling tandem at the sugar factory consists of six milling units where the cane is crushed through a succession of rollers. The hard and abrasive chopped sugarcane, as they pass through the rollers, produce crushed and dry bagasse. Figure 5(b) shows the rollers after they have been repaired by hard surfacing. Problems with milling rollers have been reported elsewhere and it has been observed that without hard surfacing, the damage to the teeth are more significant [24]. Moreover, the wearing and damage of the teeth can be attributed to the synergistic effect of abrasion and corrosion rather than to an abrasion process alone. The proposed mechanism is the cracking of the hard-facing deposits and ingress of the corrosive juice into the cracks which causes corrosion and detachment of the hard-facing deposits, leaving the steel exposed and ready to reach a state of wear [25]. The corrosiveness of the juice results due to the fact that it has pH of about 5.6 upon extraction and contains about 50 differing active microorganisms (fungi, yeast and bacteria), which when in contact with the extracted juice, can increase its acidity up to a maximum pH of 3.1 under very specific conditions. Furthermore, it was found that suspended solids along the production line like sulphate, salt and silica are ingredients to surface degradation wear mechanism [5].

3.1.4 Corrosion in pipelines
Filiform and galvanic corrosion was observed on piping systems. Filiform corrosion has been observed on pipes mainly in the evaporator section of the factory. Due to the humid environment present there, the protective coating applied over equipment such as pipe, vessels and pump casings were damaged. Galvanic corrosion was observed on flanges, valves and at welded pipes.

Erosion corrosion was also observed at the elbows of the pipelines, leading to production of leaks with time. Pitting was observed on the corrosion resistant materials, such as stainless steels, used in the manufacture of equipment, such as the crystallizer and the batch pan. Crevice corrosion was mostly observed on the flanges of piping systems. This may have been due to the improper tightening of the flange to the pipe or misalignment of the pipes. The small gaps left between the flanges, after tightening, enables the ingress of corrosive electrolyte, such as juices, and remain stagnant there for a long time causing the formation of an electrolytic cell in these sheltered areas.

3.2 Corrosion measurement

Feed table, slats and chains
As already discussed, fretting is a major type of corrosion observed on the feed table, as shown in Figure 3. The slats, table and chains are all made up of mild steel. These parts are constantly replaced after each harvest season due to their rapid degradation. The loss of thickness of the slats were measured, upon replacement. It showed that the slats abrasion corrosion rate is on average 1.89 mm/year.

Shredder and Shredder Hammers
The final preparation of the cane is performed by the shredder. It consists of 135 hammers rotating at high speed. Due to the abrasive action of the sugarcane fibres and the corrosive medium in the form of the acidic juice on the shredder hammers, the shredders’ tip were easily worn out and repaired on a weekly basis. The hammers are made up of mild steel with
the end of the tip recharged through hard surfacing. However, the shredder hammer being constantly worn out, another material, such as manganese steels which work harden under impact and compressive stresses may be used as lining instead of performing hard surfacing.

**Weighing Hopper**
The weighing hopper is used to store pre-extractor juice for a brief period of time. Every 5 tonnes of juice received by the tank causes the juice to be released in another container, from where it is pumped for further processing. As the tank is made up of mild steel, the corrosive action of the juice makes it prone to rapid degradation. The thickness of the wall of the tank was initially 8mm. The tank started to perforate 7 years later. Hence a maximum localised corrosion rate of 1.14 mm/year was observed in the weighing hopper.

**Molasses and syrup pipeline**
The molasses and the syrup pipelines were made of ss304 and were changed after every harvest season, during which they are in operation for 6 months. Hence, based on the thickness losses of the pipes, the corrosion rate of the molasses and syrup pipeline were found to be 0.616 mm/year and 0.342 mm/year respectively. The corrosion rate in the molasses pipelines were around twice higher than that in the syrup pipelines. This would be further studied using the electrochemical methods.

**Chimney**
The chimneys in the sugar factories are made of 3Cr12 steel. The exhaust gas exits the boiler via a rectangular duct making its way to the scrubber to extract the solid particle from the flue. The solid particles are then collected via a deflector found at the base of the chimney. The ID fan, found in close proximity of the scrubber, pulls the clean exhaust from the scrubber and pushes it to the chimney from which it escapes in the atmosphere. The equipment in this system is shown in Figure 6.

A typical stack monitoring result is shown in Table 3.

<table>
<thead>
<tr>
<th>Stack External Diameter, mm</th>
<th>960</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack Height, mm</td>
<td>17, 150</td>
</tr>
<tr>
<td>Number of Exhaust</td>
<td>1</td>
</tr>
<tr>
<td>Stack flue gas differential pressure, KPa</td>
<td>0.027</td>
</tr>
<tr>
<td>Stack flue gas velocity, ms⁻¹</td>
<td>6</td>
</tr>
<tr>
<td>Stack flue gas temperature, °C (inlet)</td>
<td>180</td>
</tr>
<tr>
<td>Stack flue gas temperature, °C (outlet)</td>
<td>55</td>
</tr>
<tr>
<td>Stack flue gas moisture content</td>
<td>15.40%</td>
</tr>
<tr>
<td>Stack flue gas temperature, °C</td>
<td>95.80%</td>
</tr>
</tbody>
</table>

Fig. 6 Flue Exhaust System
Corrosion in chimneys are generally caused by the flue gas aggressiveness and the temperature in the pipe [26,27]. Low temperature in the chimney results in acid dew point corrosion due to the condensation of flue gas acid species on low temperature gas path surfaces [28]. This causes severe corrosion not only of ordinary steels but even stainless steels [29]. Dew point temperature is a function of the water vapor concentration and the concentration of acid species in the flue gas [30]. For a typical flue gas, the H$_2$SO$_4$ and HCl dew points are around 136 and 72°C, respectively. At temperatures between 72 and 136°C, the H$_2$SO$_4$ condensation is the main cause of steel corrosion failure [28].

The low temperature in the duct and chimney led to dew point corrosion. Hence, it was observed that the upper end of the chimney was perforated after 4.5 years of service. The damage was expected mainly due to the condensation of the acids on the wall of the chimney. The chimney wall was of 5mm thickness and it was perforated after 4.5 years of service. The average of the maximum penetration rate of was found to be around 1.1 mm/year, based on the operating time during harvest season. One solution that can be considered is to insulate the chimney, through thermal insulation coatings for example, so that the temperature does not decrease below the dew point and eliminate dew point corrosion.

**Bagasse conveyor**

Sugar cane juice infiltrates into the conveyor chain components, such as pin, sidebar, roller and bushing. Due to the corrosive nature of the sugar cane juice, various components of the chains are corroded. This is coupled by the wear due metal-to-metal contact. This leads to reduced lifetime of the chains resulting in high maintenance costs.

### 3.3 Electrochemical and simple immersion tests

Carbon steel is being increasingly replaced by stainless steels in the sugar industry to increase the lifespan of the components from 3 to 4 years up to 10 years. The ss304 and feritic type 409L are currently popular in sugar industry in India. In Australia, South Africa and in some European countries 3Cr12 steel is commonly used in sugar mills.

**Electrochemical tests**

Electrochemical tests performed on mild steel, 3Cr12 steel, ss304 and ss316 are shown in Table 4.

<table>
<thead>
<tr>
<th>Material</th>
<th>Pre-extractor mill</th>
<th>Draft juice</th>
<th>Clarified juice</th>
<th>Syrup</th>
<th>Massecuite</th>
<th>Molasses</th>
<th>Caustic soda</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>0.39±0.06</td>
<td>0.098±0.002</td>
<td>0.10±0.01</td>
<td>0.059±0.005</td>
<td>0.171±0.006</td>
<td>0.239±0.003</td>
<td>0.25±0.01</td>
</tr>
<tr>
<td>3Cr12 steel</td>
<td>0.31±0.008</td>
<td>0.073±0.003</td>
<td>0.090±0.003</td>
<td>0.052±0.002</td>
<td>0.142±0.006</td>
<td>0.22±0.04</td>
<td>0.21±0.007</td>
</tr>
<tr>
<td>ss 304L</td>
<td>0.151±0.007</td>
<td>0.060±0.005</td>
<td>0.068±0.003</td>
<td>0.038±0.007</td>
<td>0.120±0.004</td>
<td>0.148±0.006</td>
<td>0.180±0.005</td>
</tr>
<tr>
<td>ss 316L</td>
<td>0.130±0.005</td>
<td>0.053±0.006</td>
<td>0.057±0.003</td>
<td>0.028±0.004</td>
<td>0.112±0.006</td>
<td>0.136±0.007</td>
<td>0.172±0.006</td>
</tr>
</tbody>
</table>

The Tafel tests have shown that the pre-extractor mill juice, molasses, masscuite and caustic soda are the most corrosive of the liquids tested. Pre-extractor juice has a low pH and contains field dirt, cane wax, fatty acids, bagacillo and microorganisms which raises its acidity and thereby making it highly corrosive [5]. Draft juice has higher pH than pre-extractor mill juice and consists of less impurities such as dirt, fatty acids, etc and this most probably leads to a lower corrosion rate. A similar trend in corrosion rate of pre-extractor mill juice, draft juice and clarified juice has also been obtained by Gupta et al. [31]. Syrup has the lowest corrosion rate among the different types of juices since it contains the least amount of impurities as...
compared to pre-extractor mill juice, draft juice and clarified juice [4]. Masscuite and molasses have higher corrosion rates probably due to the fact that both liquids contain bacteria which results in bio-corrosion [4]. Caustic soda is a cleaning liquid used in the cane industry. It is one of the most corrosive of the liquids tested.

It can be observed that the corrosion rate for the ss316 can be up to three times lower than that for mild steel. As shown in Table 4, ss304, which is less corrosion resistant than ss316, can be used as a cheaper alternative for less corrosive liquids, such as draft juice, clarified juice and syrup. The pipeline and components should be designed for a streamline flow and to decrease the effects of abrasion and erosion [5]. In fact, abrasion corrosion resistance of the austenitic stainless steels (ss304 and ss316) have been found to increase significantly with decrease in the velocity of the abrasive particles [32].

These results deal only with the corrosion behaviour of the metals commonly used in the cane industry. However, in the cane industry, aqueous corrosion is not the only cause of materials’ deterioration. In fact, biofilms due to the presence of microorganisms in the cane juice, the corrosion erosion phenomenon and the corrosion abrasion phenomenon should also be considered. These factors would have an influence on the corrosion rate, especially related to the stability of the passivated film on the stainless steels.

Comparing the results of the electrochemical test with those obtained through on site measurements, it can be deduced that:

- Slats had an average corrosion rate of 1.89 mm/year as measured on-site. It is very high compared to the corrosion rate of mild steel in pre-extractor juice obtained through the electrochemical methods. This is due to the fact that the slats are constantly subjected to abrasion in addition to corrosion.
- The corrosion rate in the molasses and syrup pipelines were found to be 0.616 mm/year and 0.342 mm/year respectively. The corrosion rate that were obtained through the electrochemical tests are 0.15 mm/year and 0.04 mm/year respectively. It can be deduced that the synergistic effect of abrasion has significantly increased the corrosion rate [5]. As mentioned by Durmoo et al.[5], ss304 may not be a suitable material for the pipelines in the cane industry. Since an abrasion corrosion mechanism was observed, stainless steels with higher abrasion resistance may be used, such as stainless steel type AISI 430.
- The maximum localised penetration rate in the weighing hopper was found to be 1.14 mm/year. Due to the localised corrosion, the corrosion rate was found to be nearly three times greater than that obtained through the weight loss method. It should be noted that ss316 has the highest PREN among the tested metals and it would significantly improve the lifetime of the hopper through better pitting resistance. Else, duplex steels of type AISI 2205 or austenitic ones with higher PREN, such as type AISI 317, may be envisaged [33].

Boiler

Two defect mechanisms were detected in the fire side of the boiler tubes: erosion in middle two rows and generalized erosion/corrosion, especially in the lower bends of the tubes. These are shown in Figure 7.
The erosion rate of ST35.8 steel was investigated and compared to that of AISI 1020 steel, as the reference material, and ss304 and ss316, as prospective materials. The results are shown on Table 5.

<table>
<thead>
<tr>
<th>Material</th>
<th>Average Erosion rate (mg/s)</th>
<th>Average Erosion value (mm³/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 1020</td>
<td>0.14±0.04</td>
<td>2.75</td>
</tr>
<tr>
<td>ST35.8 steel</td>
<td>0.21±0.02</td>
<td>4.38</td>
</tr>
<tr>
<td>SS 304</td>
<td>0.08±0.01</td>
<td>1.53</td>
</tr>
<tr>
<td>SS 316</td>
<td>0.052±0.006</td>
<td>1.04</td>
</tr>
</tbody>
</table>

ss316 was the most resistant material, with an erosion value of 1.04 mm³/g. The second best material observed was ss304, with an erosion value of 1.53 mm³/g. The least resistant material was ST35.8 steel. Its high erosion value was found to be approximately four times that of ss316. In fact, ss316 has been found to exhibit higher erosion resistance compared to other metals such as ss304 and AISI 1020 [21]. However, other materials have been reported to show better erosion resistance, though ss304 and ss316 have been the most commonly tested for erosion and corrosion. Other materials that have been tested for their good erosion resistance properties include stainless steel AISI 420 [22], stainless steel AISI 347, 12Cr1MoV [33,16] and nickel-aluminum bronze alloys.

### 4. Conclusion

The processing of sugar cane leads to material degradation through abrasion, erosion and/or corrosion. In this study, the common materials that may be chosen for the equipment and facilities were investigated through measurements of material losses, electrochemical tests and immersion tests.

From the measurements taken, high corrosion rates of 0.34 to 1.89 mm/year have been found in pipelines, slats, chimney and weighing hopper. From the electrochemical tests, it was observed that the pre-extractor juice had the highest corrosion rate and syrup had the lowest one. This was confirmed by the immersion tests. However, ss304 was not found to be the
best alternative material, as also noted by [5]. The effect of abrasion or erosion together with corrosion leads to a synergistic effect which results in an increase in the corrosion rate of the material. For fretting problems, with respect to the chains of the feeding table, the use of lubrication and minimising metal-to-metal contact between the chains and the other surfaces may reduce these problems. Other corrosion abrasion resistant material, such as manganese-steel may be used for the shredder hammers. The selection of a specific material for use in a particular environment in the cane industry in Mauritius would depend a lot on cost issues and on the criticality of the equipment. In such a situation, several materials may be considered as discussed in this study.

5. References

6. Van Der Linden, T. 1928. Special Case of Corrosion in the Cane Sugar Factories, Soerabaia, pp 965-968.