Corrosion behavior of 5-hydroxytryptophan (HTP)/epoxy and clay particle-reinforced epoxy composite steel coatings

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Abstract: The corrosion behavior of 5-hydroxytryptophan (HTP), and clay particulate reinforced epoxy coatings is studied on a steel substrate that is used widely in pipelines and tanks. The corrosion behavior was studied in sodium chloride (3.5 wt. % NaCl) solutions that simulate potential seawater exposure at pH 3 and 7. X-ray diffraction (XRD) and Scanning Electron Microscopy (SEM) were used for micro-structural characterization of the samples. The thermal stability was characterized using Thermogravimetric Analysis (TGA). The underlying corrosion reactions and reaction products were also elucidated via Fourier Transform Infrared Spectroscopy (FTIR). Electrochemical impedance spectroscopy (EIS) and in-situ observations of interfacial blisters were used to study the underlying degradation mechanisms. Electrochemical impedance spectroscopy revealed that for prolonged exposure of about 90 days and above, the composite materials exhibited better corrosion resistance at a pH of 3 as seen by the higher diameter of the Nyquist plot. Fewer corrosion products were observed on the scribed areas of the HTP samples in the scribe test in pH of 3 corroding environment. This signifies improved adhesion of the coatings in that environment for the HTP/epoxy coatings. The results obtained also show that a 1 mm blister size was observed in the pristine epoxy sample while no

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PUBLIC INTEREST STATEMENT
Coatings provide an effective method for the protection of surfaces that are used extensively in the infrastructure, oil and gas industry. Prior studies have shown that the service lives of epoxy-based coatings can be decreased due to the degradation of epoxy coatings in different working environments (with different temperature, moisture, corrosive element). There is therefore a strong interest in the development of novel coatings that can extend the service lives of such epoxy-coated structures.

This paper therefore presents the results of the corrosion behavior of epoxy-based composite coatings with two different fillers (clay particles and 5-hydroxytryptophan (5-HTP)). Corrosion phenomena are studied in environments that simulate potential seawater environments (3.5 wt % NaCl). A combination of ex-situ and in-situ microscopic observations is used to study the underlying corrosion behavior.
blisters were observed in the clay/epoxy and HTP/epoxy samples exposed at pH of 3. In the pH 7 environment, the EIS experiment revealed the presence of blisters with diameters in the range of 1–4 mm, after exposure for 90 days. The implications of the results are discussed for the corrosion protection of steel surfaces with composite coatings.

Subjects: Coatings & Thin Films-Materials Science; Composites; Corrosion-Materials Science; Polymers & Plastics; Surface Engineering-Materials Science

Keywords: epoxy composite coatings; steel substrate; corrosion degradation behavior

1. Introduction
Coatings provide an effective method for the protection of surfaces especially pipelines, and storage tanks that are used extensively in the infrastructure, oil and gas industry (Se, 2010). Coatings also provide physical barriers between steel structures and their surrounding environments. There is therefore a strong interest in the development of novel coatings that can extend the service lives of pipelines, storage tanks and offshore structures in the oil and gas industry (Se, 2010), where billions of dollars are lost annually due to corrosion degradation phenomena (Rahbar et al., 2008). However, a coated steel structure exposed directly to the harsh sea water can be hit or bombarded by floating objects that leaves impact defects on the coating surface which can influence corrosion of a neatly coated area of a steel substrate (Madlangbayyan et al., 2018). Hence, it is necessary to perform scribe test to evaluate the behavior of the coating at the coating/metal interface near the scribe. According to (Yasuda et al., 2001), when a coating surface is damaged, the exposed coating/metal interface should be subject to investigation and the passivating or anticorrosive effect of the coating is investigated to ascertain the extent of the corrosion-induced delamination of the coating near the damaged area.

The pores at the crossed linked junctions in a cured epoxy coating can also assist in migration of absorbed water and other species such as chlorides and hydroxide ions into the epoxy/metal interface. This leads to the initiation of corrosion in the metallic substrate, and ultimately to the delamination of the coating from the substrate (Khodair et al., 2018) (Rathish et al., 2013). Blistering is the most common mode of failure which is caused by the migration of liquid through the coatings, as a result of the induced osmotic effect (Rathish et al., 2013) (Dana et al., 2013). Microbes can also attack the hydrocarbon and non-hydrocarbon fuel molecules, leading directly to a change in chemical properties and performance (Gaylarde et al., 1999).

Tank venting, which is essential for preventing tanks from collapsing under atmospheric pressure, is a major entry route for contaminating microbes (Gaylarde et al., 1999)(Turkiewicz et al., 2013). Microbes can also be transported from refinery tanks or barges, through pipelines and terminal tanks, throughout the fuel distribution system. In any case, relatively small volumes of water can support localized pockets or niches of microbial growth that lead ultimately to microbial corrosion.

Furthermore, internal corrosion can occur when the pipeline walls, and storage tank walls are exposed to water and contaminants such as oxygen, hydrogen cyanide, carbon dioxide and chlorides (Khodair et al., 2018). Prior studies have shown that the service lives of epoxy-based coatings can be decreased due to the degradation of epoxy matrices in different working environments (temperature, moisture and corrosive elements) (Khodair et al., 2018, Turkiewicz et al., 2013). Their applications are also limited by their susceptibility to damage by surface abrasion and wear (Suresha et al., 2018, Gledhill et al., 1978) as well as the initiation and propagation of cracks (Dana et al., 2013). Such processes can introduce localized defects into coatings, which accelerate the ingress of water, oxygen and chemical species into the metallic substrates, thus resulting in their localized corrosion (Rathish et al., 2013).
The above challenges have stimulated researchers to explore alternative coatings that can be used for the protection of steels that are used extensively in the pipeline industry and structural applications (Zaarei et al., 2010).

Some other researchers have used alternative methods such as surface nanocrystallization of steels by nano-structuring the surface layer (Olugbade & Lu, 2019) and observed enhanced corrosion resistance and the micro-hardness of the treated samples improved from 215 to ~310 HV (Olugbade & Lu, 2019)

Recent discoveries indicate that the inclusion of inorganic fillers effectively enhances the corrosion protection of pristine polymers such as conductive, thermoplastic and thermosetting polymers on cold rolled steel (Huang et al., 2008). Epoxy coatings that contain fillers have also been shown to enhance corrosion protection (Zaarei et al., 2010). They may also reduce the tendency of coatings to blister or delaminate (Ates, 2016). Montmorillonite, which has a plate-like structure, is often used as a filler to increase the diffusion pathways, and thus reduce the permeability of corrosive agents within the coating material. 5-hydroxytryptophan (5-HTP) have also proven to be an effective corrosion inhibitor on bare steel, as shown in the work by E. B. Ituen et al. (2015) (E. B. Ituen et al., 2015). Developed organically as a food supplement (to fight depression in humans), 5-HTP is gradually being considered as an anti-corrosion filler due to its stability in acidic environments (E. B. Ituen et al., 2015).

This paper therefore presents the results of the corrosion behavior of epoxy-based composite coatings with two different fillers (clay particles and 5-hydroxytryptophan (5-HTP)). Corrosion phenomena are studied in environments that simulate potential seawater environments (3.5 wt % NaCl). A combination of ex-situ and in-situ microscopic observations is used to study the underlying corrosion behavior. From the literature, it is known that corrosion resistance of a coated metal is dependent on some key factors including the ability of the top coating to resist salt intrusion, to resist the inflow of water and other corrosive chemicals in a corroding environment, the effects of passivating elements, the extent of coating adhesion to the metal, and how oxidized the coating surface is (Yasuda et al., 2001). This study seeks to evaluate the ability of the produced composite coatings to resist the inflow of water and other corrosive chemicals in a corroding environment, the effect of passivating elements, and the extent of coating adhesion to the metal. Electrochemical impedance spectroscopy (EIS) and scribe tests are used to evaluate the blistering and creepage of the coated samples. The underlying corrosion reactions and reaction products are also elucidated via Fourier Transform Infrared Spectroscopy (FTIR) and X-Ray Diffraction (XRD). Finally, the thermal stability of the coatings is evaluated to ascertain the weight loss patterns in the different composites. The implications of the results are discussed for the corrosion protection of steels. This research would potentially find application in the infrastructure, biotechnological and above all the oil and gas industry where the corrosion resistance and good adhesion of coatings are of great importance.

2. Materials and experimental methods

2.1. Materials

Sigmacline 523 (Sigmaclining SF 23) hardener and base obtained from Sigmakalon Belgium N.V Tweemontstraat 104, 2100 Deurne-Antwerpen was used to produce the epoxy. The epoxy had a molecular weight of ≤700 g/mol and a specific density of 1.48 g/cm³. The clay particles, Cloisite 30B (C30 B), were natural montmorillonite modified with methyl-tallow-bis-3-hydroxyethyl quaternary ammonium salt (procured from Southern Clay Products Inc., Texas, USA). The cation exchange capacity (CEC), which determines the amount of the alkylammonium ions present between the clay-clay layers of C30B, was 90 meq/100 g. The d-spacing of the (001) plane was 1.85 nm, and the density was 1.98 g/cm³. The average particle size was about 5 µm. The 5-Hydroxytryptophan (obtained from Sigma Aldrich EMD Millipore Corp, Billerica, MA, USA) with
an average particle size of ~17 μm had a molecular weight (Mw) of 220.22 g/mol and a density of 1.484 g/cm³.

Figure 1 presents the Scanning Electron Microscope, SEM micrographs of the two fillers. The X65 low carbon steel was obtained from the Schiabit Construction Company, SCC, Bwari, Abuja, Nigeria. The actual chemical composition of the low carbon steel is presented in Table 1.

2.2. Experimental methods
The steel samples were cut into 40 mm x 20 mm x 3 mm with mark V series machine. This was done using a size 64 silicon carbide blade. A cooling fluid was used to cool the samples during the cutting process, in an effort to prevent work hardening of the samples during specimen fabrication. The steel substrate had a Rockwell C hardness of about 10.

2.3. Epoxy composite processing
Epoxy composites with 3 wt. % C30B and 5-HTP were used. It has been found in literature that clay filler gives their optimum protection at 3 wt.% (Systems et al., 2017)(Kusmono et al., 2013) (Khanbabaei et al., 2007). The 3 wt% of cloisite 30B clay was added to the epoxy base and stirred with a magnetic stirrer for 2.5 hours at a rate of 1500 rpm. This was done at 50°C to enable a uniform dispersion of the clay particles. The resulting mixture was then degassed in a vacuum oven for 2 minutes, before adding a stoichiometric quantity of the curing agent and mixing with a spatula. A final degassing was then carried out in the vacuum oven at 50°C for a period of 1 minute. The stoichiometric mixture of epoxy resin and base was 2:1. The same procedure was repeated for 5-Hydroxytryptophan (5-HTP). The preparatory process is illustrated in Figure 2.

According to ASTM D823-17 (ASTM International, 2018), a hand-held spray gun (Devilbis Finishline 4FLG-670 solvent-based 4VLP Gravity Feed paint Gun, Worcester, MA, USA) was used to apply the coatings. The coating thickness of ~0.5 mm was controlled by: the transverse speed of the gun; the number of passes of the gun; the fluid delivery rate of the gun; the viscosity of the material. The coating mixtures were diluted by adding 20 wt% of thinner to increase the flow rate. The mixtures were then sprayed for durations of about 10 seconds during each pass. The total of five transverse passes was used in spraying at a pressure of 0.1034 MPa/15 psi.

The microstructures of the pristine epoxy, epoxy/clay and 5-HTP/epoxy composites were characterized in a scanning electron microscope (Carl ZEISS model evo10LS-EDAX) that was operated at 20 kV. Optimal Fourier Transform Infra-Red (FTIR) spectra were obtained in the region in the region of 4000–500 cm⁻¹ (Thermo-Scientific FTIR (Model: Nicolet ISS, USA) to identify the functional groups of the coatings (Theingi et al., 2019). The structure of the composites was characterized using a Rigaku X-Ray diffractometer using Cu Kα radiation, measured at 30 kV and 15 mA. The data were recorded within a 2θ range of 5–10°, with step size of 0.03° and a count speed of ~0.5°/min.
| Steel samples          | C  | Si  | Mn  | P  | S  | V  | Nb | Ti | Fe  |
|------------------------|----|-----|-----|----|----|----|----|----|-----|
| Low Carbon Steel       | 0.12 | 0.45 | 1.60 | 0.025 | 0.015 | 0.15 | 0.15 | 0.15 | 97.36 |
2.4. Scribe/knife tests corrosion experiments

The susceptibility of the coatings to blistering or adhesion was characterized using scribe testing. The scribe tests were performed in accordance with ASTM 870–02 (Coatings et al., 2002) and ASTM 1654 procedures (Surfaces et al., 2018, Abdel-samad et al., 2014). A knife with a width of 0.58 mm was used to conduct the test at room temperature (~25°C). The scribe penetrated all the organic coating layers on the samples. After scribe testing, samples were immersed in acidic and neutral 3.5 wt. % NaCl solutions in deionized water. The pH of the solution was controlled by adding 1 M HCL into the NaCl solution until the pH of the solution was adjusted to pH of 3.

Photographs of each sample were obtained at different time intervals up to a period of 90 days of exposure to 3.5 wt. % NaCl acidified to a pH of 3 and a neutral solution. These were used to characterize the extent of blistering on the scribed and exposed surfaces. The scribed samples were also investigated for creepage and blistering around the scribed and un-scribed areas of the coated samples. This was done in accordance with the ASTM 1654–08 code. The samples were each rinsed at the end of each experiment, using a gentle stream of water at room temperature (25°C). The loose coatings along the scribed area were then removed with a knife (within 15 minutes of exposure) prior to the investigation of creepage.

The discolored areas of the samples, due to corrosion, were characterized in accordance with the ASTM 1654–08 code. Six measurements of the widths of the corrosion zone were obtained at uniform distances along the scribed area, in accordance with the ASTM standard 1654–08. The arithmetic mean of the measured zone (for each sample) was also computed. This was used to calculate the rust creepage (C) given by equation (1):

\[
C = \frac{w_e - w}{2}
\]

where \( w_e \) is the mean overall width of the corrosion zone and \( w \) is the width of the original scribe.

2.5. Electrochemical impedance spectroscopy (EIS)

In order to prepare the epoxy-coated mild steel panels for electrochemical testing, an electrochemical masking tape (SKU 990-00254, by Gamry Instruments, Worcester, MA, USA) was used to define the working area of the coated metal substrates during the tests. Microstructures of the coated samples are presented in Figure 3. Electrochemical measurements were carried out using a Versa STAT 3 studio (Princeton Applied Research software). The Versa STAT studio was equipped with a 3 electrode system in a KO47 corrosion kit. The epoxy-coated steel coupons served as the
working electrode. Ag/AgCl was used as the reference electrode, while a graphite rod served as the counter electrode with an exposed area of 1 cm² that defined the working electrodes.

EIS was used to study the corrosion resistance of the coated panels in which the barrier properties of all the different composite coatings were investigated. EIS was performed in electrolytes that contained 3.5 wt. % NaCl with pH values of 3 and 7. The EIS measurements were obtained from the coated immersed steel samples using the Versa STAT studio system. The steel was polarized at 10 mV. An open circuit potential (Eoc) was applied with an alternating current (AC) signal with frequencies between 100 kHz to 10 mHz (10 points per decade).

3. Results and discussion

3.1. Fourier transform infrared spectroscopy (FTIR)

Functional group analysis was carried out using Fourier Transform Infrared Spectroscopy (FTIR). This was used to examine possible interactions between the composites and the epoxy. The FTIR peaks of 1507, 1559, 1636, 1653, 1654, and 1400–1000 cm⁻¹ were associated with aromatic rings for pristine epoxy, clay/epoxy, and HTP/epoxy, as shown in Figure 4. The peak at 3481 cm⁻¹ (in the 5-HTP/epoxy spectra) indicated the presence of 5-HTP in HTP/epoxy. The absorption band 668 cm⁻¹ indicated the presence of aromatic C-H bending. The peaks observed at 2343 and 2360 cm⁻¹ indicate the presence of CO₂.

HTP/epoxy and clay/epoxy had similar functional groups with similar absorbance signifying a similar adhesion behavior of the two composites due to the presence of O-H bonds for bonding with steel.

3.2. Electrochemical impedance spectroscopy (EIS)

The results of the EIS are presented in Figure 5 in which the Nyquist plots are presented for the three types of coated steel surfaces. The Nyquist plots are characterized by semicircles with inductive loops. This is attributed to the adsorption of an intermediate product during corrosion reaction. In general, the higher the diameter of the semicircle (the charge transfer resistance), the lower the corrosion rate. The radii of the plots decreased with increasing immersion time. This is consistent with the decrease in the corrosion resistance of the coated steel surface. All the samples were found to exhibit semicircular loops at different impedance values. However, the HTP/epoxy coatings exhibited the highest charge transfer resistance during the first 12 days of environmental exposure. The impedance plots also revealed the dominance of coating capacitance in the high-frequency regime and coating resistance in the low-frequency regime of about 2 x 10⁵ Ωm². This is attributed to the thickness of the coatings, which were about 0.5 mm thick. The second semicircles (observed at the low-frequency regime in some of the samples) suggest that the electrochemical reactions occur at the metal/coating interfaces. At this stage, the diffusion of electrolytes into the coating is complete. The electrolyte phase also reaches the metal/coating interface, prior to the growth of the blisters as shown in Figure 6 (interfacial cracking and delamination), and the corrosion of the steel substrate (Figure 5(a–f)).
The fitted plots for 97 days of exposure are presented in Figure 5(e,f). A 1 mm size of blister was observed for epoxy samples exposed at pH of 3 while all other samples blistered at different sizes ranging from 1 mm, 2 mm to 4 mm in the corroding environment of pH = 7 after 90 days of experiment. The result showed that the composite’s corrosion protection generally depends on the pH of the corroding environment. The Nyquist plots were fitted using a non-linear regression analysis.
3.3. Scribe testing
The crepage and ratings data obtained from scribed areas on samples exposed for 90 days are summarized in Table 2 (for pH of 7) and Table 3 (for pH of 3). The HTP samples exhibited good crepage/ratings. The best ratings were obtained for the acidic environment with a pH of 3, with no blistering occurring at the scribed areas as shown in Figure 7. Furthermore, pristine epoxy and epoxy/clay samples exhibited the lowest crepage/ratings, with no blistering in the scribed areas. These results reveal that HTP/epoxy coatings exhibited better adhesion (Yasuda et al., 2001) which is a very important parameter of corrosion resistance of a coated metal.

(Tables 2 and 3). Interestingly, the corrosion products of samples in the corrosion environment with a pH of 3 had less corrosion products at the scribe area which is reflected by the crepage rating in Table 2 and the image in Figure 7. It can also be deduced that the interface at HTP/epoxy had a better adhesion and possibly offered passivating effect on the metal than clay/epoxy and pristine epoxy. Prior work by (E. Ituen et al., 2017, Yasuda et al., 2001) on the corrosion inhibition of 5-HTP in acidic environments, and the effect of scribe test on coated metal had similar results. According to (Yasuda et al., 2001), as soon as a sample is scribed, the coating/metal interface becomes an area of investigation.

3.4. X-ray diffraction (XRD) analysis
Typical XRD peaks obtained for the HTP Epoxy, clay epoxy and pristine epoxy structures are presented in Figure 8. The results are consistent with prior report in the literature (Zaarei et al., 2010). The interlayer d-spacing (d_{002}) of pure C30B as reported by Zaarei et al. (2010), estimated that the position of the intense diffraction peak of the (100) plane, is 1.88 nm. In addition, the weak peak of the (200) plane is placed at higher diffraction angles, corresponding to a d-spacing (d_{002}) of 0.94 nm. There is also a shift to lower 2θ, from 10° in pristine epoxy to 9.9° in HTP/epoxy and clay/epoxy, which had a higher intensity.

3.5. Thermo-gravimetric analysis (TGA)
Figure 9 presents the thermogravimetric analyses of the pristine epoxy, epoxy/clay and epoxy/HTP and their decomposition temperature.

Figure 6. Blister formation after 97 days of exposure at different pH during EIS: (a) HTP coating (pH = 3); (b) clay coating (pH = 3); (c) epoxy coating (pH = 3); (d) HTP coating (pH = 7); (e) clay coating (pH = 7), and (f) epoxy coating (pH = 7).
Table 2. Mean creepage from scribe areas on samples observed for 90 days for pH of 7 (E, pristine epoxy sample, C, epoxy/clay samples and HTP, 5-Hydroxytryptophan samples.)

| Coatings | Duration (days) | Creepage | Rating |
|----------|----------------|----------|--------|
| E1       | 90             | 0.91     | 8      |
| E2       | 90             | 0.30     | 9      |
| C1       | 90             | 1.10     | 7      |
| C2       | 90             | 0.86     | 8      |
| HTP 1    | 90             | 0.41     | 9      |
| HTP 2    | 90             | 0.36     | 9      |

Table 3. Mean creepage from scribed areas on samples immersed at pH of 3 for 90 days

| Coatings | Duration (days) | Creepage | Rating |
|----------|----------------|----------|--------|
| E1       | 90             | 0.42     | 9      |
| E2       | 90             | 0.20     | 9      |
| C1       | 90             | 0.30     | 9      |
| C2       | 90             | 0.10     | 9      |
| HTP1     | 90             | 0.50     | 9      |
| HTP 2    | 90             | 0.06     | 9      |

According to the ASTM 714–02 Standard, the scribed areas of all the samples had no blisters.

Figure 7. Photographs of scribed samples exposed to acid (pH = 3: (a), (b), (c)) and neutral (pH = 7: (d), (e), (f)) NaCl solutions for 90 days; Neat epoxy (a, d); HTP-Epoxy (b, e) and Clay-Epoxy (c, f).
Figure 8. XRD patterns obtained from HTP/epoxy, Clay/epoxy and pristine epoxy samples.

Figure 9. TGA plots obtained from pristine epoxy, clay/epoxy and HTP/epoxy.
Pristine epoxy was used as a reference. This was carried out in nitrogen at room temperature (25°C) at a heating rate of 10°C/min. The corresponding mass loss of moisture was seen to be about 3.5% HTP/epoxy, 4% for clay/epoxy and 6% for pristine epoxy.

The initial degradation temperatures, cited as the characteristic temperature for assessing the thermal stability, were measured by determining the temperature at which 5% degradation occurs (Gu & Liang, 2003). Pristine epoxy polymer matrix decomposed at 366.6°C, epoxy/clay at 368.6°C and HTP/epoxy at 370.1°C at heating rate of 10°C/min.

It has been established in the literature that the inclusion of fillers increase the thermal stability of the composite system (Dzuhri & Yuhana, 2015; Gu & Liang, 2003). The results revealed that the inclusion of montmorillonite and 5-hydroxytryptophan improved the thermal degradation of the composites.

3.6. Implications
The implications of the current work are quite significant. First, the results show that fillers such as 5-HTP and cloisite clay particles can be used to enhance the corrosion resistance of epoxy-based coatings in acidic or neutral environments. However, the enhancements depend on the pH, as shown in the current work. Similar improvements have been reported by other researchers [10] that have used fillers to enhance the corrosion resistance of epoxy-based coatings. The improvements are attributed to the interactions between the filler materials and aqueous species.

In the case of the cloisite clay particles and the 5-HTP particles, the fillers behave in ways that can delay the transport of aqueous species to the steel substrate. In-situ reactions and chemisorption processes can also occur in ways that reduce the transport of aqueous species to the substrate. Further work is clearly needed to provide mechanistic insights into such phenomena. In any case, the results of the current study suggest that cloisite clay particles and the 5-HTP fillers can be used to enhance the corrosion resistance of epoxy coatings on mild steel substrate that was used in this study.

4. Conclusions
This paper presents the results of an experimental study of corrosion inhibition of mild steel that was coated with epoxy and epoxy composites that contained 5-HTP and cloisite 30B clay micro-particles. Salient conclusions arising from this study are summarized below.

The electrochemical impedance spectroscopy and the scribe test revealed that corrosion is pH-dependent. Furthermore, less corrosion products were seen on the scribe areas of the HTP samples in the scribe test in the pH of 3 corroding environment. This signifies a better adhesion of coating in that environment for HTP/epoxy coatings. This was also confirmed by Figure 6 where just 1 mm size of blister was observed for epoxy sample exposed at pH of 3 while all the other sample blistered at different sizes ranging from 1 mm, 2 mm and 4 mm in the corroding environment of pH = 7 after 90 days of EIS experiments.

The TGA results reveal that the HTP/epoxy samples had the least mass loss due to moisture content compared to clay/epoxy and pristine epoxy. This possibly might be due to the fact that the blockage of the polymer gallery by the fillers was more evident in HTP in the polymer coating. Hence, the HTP/epoxy composite coating has a better heat resistance than the clay/epoxy and pristine epoxy. The FTIR spectra reveal the presence of O-H bonds in HTP/epoxy which acts as the bonding site of the coating just like in clay/epoxy. Hence, HTP could be potential filler for epoxy coatings for use in coating steel pipes and tanks. It is recommended that further work should be done on the char yield to determine the flame resistance of the HTP composite. One of the limitations of this work was that the TGA test was performed only in nitrogen environment. Further work needs to be done to perform TGA in air for better comparisons. The enhanced thermal stability of HTP/epoxy nanocomposites, in combination with the high corrosion protection, makes them attractive candidates for various coating applications.
Nomenclature

- **HTP**: Hydroxyltertophnan
- **NaCl**: Sodium Chloride
- **XRD**: X-ray Diffraction
- **TGA**: Thermogravimetric Analysis
- **FTIR**: Fourier Transform Infrared Spectroscopy
- **EIS**: Electrochemical Impedance Spectroscopy
- **pH**: Hydrogen ion potential
- **C30B**: Cloisite 30B
- **CEC**: Cation Exchange Capacity
- **SEM**: Scanning Electron Microscope
- **SCC**: Schiabit Construction Company
- **ASTM**: American Society for Testing and Materials
- **HCl**: Hydrochloric acid
- **AC**: Alternating Current
- **E_ac**: Open Circuit Potential

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Declaration of interest statement

Authors declare that they have no competing financial interest or personal relationship that could have appeared to influence the work reported in this paper.

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