Suitability of carbon fiber-reinforced polymers as power cable cores: Galvanic corrosion and thermal stability evaluation


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The increasing demand for electrical energy and the difficulties involved in installing new transmission lines presents a global challenge. Transmission line cables need to conduct more current, which creates the problem of excessive cable sag and limits the distance between towers. Therefore, it is necessary to develop new cables that have low thermal expansion coefficients, low densities, and high resistance to mechanical stress and corrosion. Continuous fiber-reinforced polymers are now widely used in many industries, including electrical utilities, and provide properties that are superior to those of traditional ACSR (aluminum conductor steel reinforced) cables. Although composite core cables show good performance in terms of corrosion, the contact of carbon fibers with aluminum promotes galvanic corrosion, which compromises mechanical performance. In this work, three different fiber coatings were tested (phenol formaldehyde resin, epoxy-based resin, and epoxy resin with polyester braiding), with measurements of the galvanic current. The use of epoxy resin combined with polyester braiding provided the best inhibition of galvanic corrosion. Investigation of thermal stability revealed that use of phenol formaldehyde resin resulted in a higher glass transition temperature. On the other hand, a post-cure process applied to epoxy-based resin enabled it to achieve glass transition temperatures of up to 200°C.

1. Introduction

Electricity use in Brazil has been increasing steadily over the past decade. According to the Brazilian Ministry of Mines and Energy (MME), consumption has risen from 28.51 × 10⁹ toes (tonne of oil equivalent) in 2000 to 42.86 × 10⁹ toes in 2012 [1]. Energy supply companies are therefore developing new transmission cables in order to decrease sag and to improve creep resistance under high current loads. This will enable greater distances between towers and help to reduce costs. The use of composites with thermosetting matrices reinforced with continuous carbon fibers enables substantial weight reduction combined with high strength- and stiffness-to-weight ratios, low thermal expansion coefficients, excellent fatigue properties, and good corrosion resistance [2–6]. These benefits, allied with the ability of the pultrusion process to produce materials with high strength-to-weight ratios and dimensional stability, make these cables suitable replacements for traditional steel core transmission cables, reducing the sag between towers and improving electricity transmission [4,7,8]. In other applications, the high corrosion resistance of these materials makes them an attractive alternative for retrofitting steel structures, improving the stiffness of steel bridge girders [9,10], strengthening concrete [11,12], and replacing steel cables in bridges and other civil structures [13]. However, the most important issue concerning their mechanical performance is the occurrence of galvanic corrosion between carbon and aluminum, which can compromise cable performance for the purposes of the application proposed in this work [14–16]. According Davis [17], under most environmental conditions normally encountered in service, aluminum and its alloys are the anodes in galvanic cells with most others metals, protecting them by corroding sacrificially. This corrosion is more severe in solutions of halide salts as chloride solutions. It is known that graphite/aluminum composites exhibit accelerated corrosion in marine environments when graphite fibers and aluminum are exposed simultaneously. According to Oldfield [18], galvanic corrosion is caused by the difference in potential between two conducting materials. The nobler material acts as a cathode, while the more reactive material...
acts as an anode, which corrodes. According to the galvanic series (ASTM: G82), aluminum is a reactive metal that should have low corrosion resistance. Nevertheless, a thin, compact, and adherent aluminum oxide film is formed on the surface, which provides aluminum alloys with high corrosion resistance. Additionally, the galvanic series shows that the galvanic effect will be greater for substances that are farther apart in the series. Aluminum and carbon (graphite) are distant from each other, so it is expected that galvanic corrosion will be an important issue in applications involving these two materials, affecting the lifetime and reliability of carbon fiber-reinforced polymer (CFRP) cores of power transmission cables. The occurrence of galvanic corrosion between CFRP and aluminum is well known in the aerospace industry [16,19,20], and similar effects have been observed for CFRP used with concrete and steel in civil engineering [9,11,12,14,21]. On the other hand, several galvanic pairs can show behavior different to that expected from the galvanic series, due to environmental effects and the cathodic/anodic surface ratio [22,23]. To minimize corrosion of aluminum in contact with more cathodic material, the ratio of the exposed area of aluminum to that of the more cathodic material should be kept as high as possible. Paints and other coating can also be applied to both the aluminum and the cathodic material or to the cathodic material alone [17]. Ireland et al. [24] investigated the occurrence of galvanic corrosion between aluminum 7075 alloy and glass fiber-reinforced polymer made from epoxy resin modified with multi-walled carbon nanotubes (MWCNTs), and attributed galvanic corrosion to the presence of the MWCNTs. In other work, aluminum-based matrix metal composites were found to be more susceptible to corrosion attack, with Al/SiC composites exhibiting strong corrosion in NaCl environments due to galvanic coupling [25].

This work investigates galvanic corrosion involving aluminum 1350 and carbon fiber-reinforced polymers, and assesses improvements in corrosion resistance achieved by applying protective layers of phenol formaldehyde resin or epoxy-based resin. A suitable protective surface layer can act as a barrier, altering the corrosion rate [26] and extending the service lifetime. The thermal stability of CFRP composites is also evaluated, because composite core transmission cables can reach temperatures of up to 200 °C during energy consumption peaks.

2. Materials and experimental procedure

Pultruded rods composed of three different polymeric matrices reinforced with continuous carbon fibers were manufactured using phenol formaldehyde resin (D26-GPB, Georgia-Pacific), epoxy-based resin (CY179CH, Huntsman), and epoxy-based resin with polyester braiding. Samples of aluminum 1350 that complied with the ASTM: B231 standard were provided by Alubar. This material is often used as an electrical conductor in traditional transmission cables. During the manufacturing process, the cast ingot is reduced by rolling to decrease the cross-section and is then submitted to forging to obtain a diameter of 0.5 mm. Final thermal treatments are conducted before tempering, according to the application.

Phenol formaldehyde resin, epoxy-based resin, and epoxy resin with polyester braiding were applied to the aluminum surface in order to study their effectiveness in preventing galvanic corrosion.

2.1. Electrochemical corrosion tests

The electrochemical corrosion test apparatus is illustrated in Fig. 1. A PAR/EG&G Model 283 potentiostat/galvanostat was used to perform zero resistance ammeter (ZRA) tests in order to evaluate the effectiveness of the different coatings for prevention of galvanic corrosion between the carbon fiber-reinforced polymer and the aluminum. These tests were conducted in accordance with the ASTM: G71 standard procedure. In this, the working electrode and the counter-electrode were replaced by specimens of aluminum and carbon fiber, and the electrical current density between them was monitored. The ZRA tests were carried out in neutral 3.5 wt.% NaCl solution (artificial seawater). Five tests were performed; two of the results (the highest and lowest values) were discarded and the remaining three were used to calculate the average values. During the test, the electrolyte was not moved or aerated. According to Möller et al. [27], seawater is not easily simulated in the laboratory for corrosion-testing purposes, due to the complexity of the variables involved, such as dissolved oxygen levels, salinity, and concentrations of minor ions, biological activity, and presence of pollutants. A 3.5 wt.% NaCl solution is normally used to represent seawater, and is known to be more aggressive. In natural seawater, the presence of calcium and magnesium acts to provide a physical barrier against oxygen diffusion, hence decreasing the corrosion rate.

The microstructures of the aluminum and carbon fiber samples with different coatings were evaluated using optical microscopy (Axiophot, Zeiss) and scanning electron microscopy (Model 5800LV, JEOL).

2.2. Thermal analyses

Thermogravimetric analyses (TGA) were performed using an SII Extra instrument (Seiko Nanotechnology) operated with a constant flow of nitrogen (50 mL/min). Samples (~20 mg) of the two pultruded systems (epoxy and phenol formaldehyde resins reinforced with continuous carbon fibers) were placed in a standard platinum pan and a dynamic analysis was performed by heating from 50 to 800 °C at a rate of 10 °C min⁻¹.

Dynamic mechanical analysis (DMA) was performed with a DMTA-3E Test Station (Patel Scientific). Samples of the same two pultruded systems were measured in dual cantilever bending.
mode, using a frequency of 1 Hz and heating from 30 to 300 °C at a constant rate of 5 °C min⁻¹.

3. Results and discussion

The objective of this work was to study galvanic corrosion prevention using a protective layer, as well as the thermal stability of the layer, envisaging the use of a pultruded aluminum conductor composite core (ACCC) as a replacement for traditional steel ACSR power cables. The two systems to be used as cores of ACCC power cables are illustrated in Fig. 2 and Fig. 3. Two different geometries were employed, corresponding to the Raven and Linnet core configurations of traditional aluminum and steel-reinforced cables.

3.1. Corrosion performance

Scanning electron micrographs of the carbon fiber-reinforced polymer submitted to a pultrusion process with epoxy resin are shown in Fig. 4, where it is possible to observe raw fibers, the epoxy coating, and continuous fibers embedded in the epoxy coating. The composition of the samples was approximately 80 wt.% of carbon fiber and 20 wt.% of resin.

Fig. 5 displays the current density measurements for 1350 aluminum alloy in 3.5 wt.% NaCl solution. During the manufacturing process, an aluminum ingot was firstly obtained, followed by the rolling and drawing procedures. Evaluation was made of galvanic corrosion for the CFRP in contact with aluminum samples under three conditions (ingot, rolled, and drawn samples), according to the ASTM: G71 standard procedure.

According to Wolstenholme [29], in corrosion evaluation a galvanic current generated by dissimilar metals immersed in an electrolyte can only be measured correctly with a zero electrical resistance (using a zero-resistance ammeter for measuring large galvanic currents) [30]. The results of the galvanic current measurements (Fig. 5) revealed minor differences in the galvanic currents obtained for the different aluminum specimens and the CFRP. A higher galvanic current was developed during the initial coupling period, after which a plateau was reached. The galvanic current density is shown in Fig. 5 (with a 95% confidence interval). It can be seen that the current ranged between 20 and 25 µA cm⁻² for all the aluminum samples. Wang et al. [31] studied corrosion in carbon fiber metal laminates and observed a galvanic current of 20 µA between 2024-T3 aluminum alloy and CFRP. When a composite coating was applied, there was a decrease in the galvanic current to 30 nA. On the other hand, in a study of aluminum-based metal matrix composites reinforced with carbon fibers, Coleman et al. [32] observed high galvanic currents of 465 and 320 µA for 357-aluminum alloy/carbon fiber and 2124-aluminum alloy/carbon, respectively.

In this work, the galvanic current between drawn aluminum wires and CFRP in a 3.5 wt.% NaCl solution (artificial sea water) was measured for up to 60 h. Three samples were used for each condition. The behavior of the galvanic current was similar to that described previously. The average value was around 25 µA (Fig. 6) for both immersion times (16 and 60 h), confirming that a plateau was reached.

Fig. 2. Single composite core manufactured by the pultrusion process.

Fig. 3. Twisted composite core manufactured by the pultrusion process.

Fig. 4. Scanning electron micrographs of the carbon fiber-reinforced polymer (CFRP), showing raw fibers, epoxy-based polymer, and fiber with epoxy coating.
Optical microscopy images of the drawn aluminum samples after galvanic coupling are shown in Fig. 7 for immersion times of 16 and 60 h. Pitting corrosion can be seen, resulting from the dissolution reactions that occurred as the current density was increased. The results obtained here indicated that there was no degradation of the carbon fibers.

The results of the ZRA tests using the drawn aluminum wires and the CFRP are shown in Fig. 8. Three configurations were tested, using CFRP produced with phenol formaldehyde resin, epoxy resin, and epoxy resin plus polyester braiding. The carbon fiber composites with the phenol formaldehyde resin matrix provided less effective protection against galvanic corrosion (Fig. 8a), because the galvanic current was higher than that measured between aluminum and raw carbon fibers. This can be explained by the presence of exposed carbon fibers, enabling a galvanic current to flow between the materials. Fig. 9 shows an SEM image of raw carbon fibers in the phenol formaldehyde resin matrix after ZRA testing for 16 h. There was probably a synergistic effect involving exposure of the raw carbon fibers and degradation of the phenol formaldehyde resin, resulting in higher galvanic coupling current flow. The higher current density indicated a faster corrosion rate, reflecting easier corrosion in seawater.

Greater galvanic corrosion resistance was achieved for the carbon fiber composite with an epoxy-based matrix. The current density flow between the aluminum and the CFRP decreased to $6.1 \pm 0.6 \mu \text{A cm}^{-2}$ (Fig. 8b), indicating that there was less stimulation of galvanic corrosion, compared to aluminum and the raw carbon fibers. Nonetheless, although the epoxy coating provided a degree of protection, there was probably some contact between the raw fibers and the aluminum. The integrity of the epoxy surface coating is shown in the scanning electron micrograph of Fig. 10, where the arrows indicate the presence of defects. It is important to emphasize that the measured current is acceptable in terms of corrosion, because it is of similar magnitude as that of the material in a passive state. According to [33] normally, a good passivity should correspond to a relatively drastic decrease in corrosion rate of the immersed metal and could correspond to a corrosion rate of a few microamperes per square centimeter instead of mA/cm$^2$. Liu et al. [34] studied the effect of natural inhibitors on corrosion of AA7075 alloy exposed in a 3.5% NaCl solution and reported that the corrosion current decreased from 52 to 3 $\mu$A cm$^{-2}$ when 1000 ppm of an organic inhibitor was used. There was therefore an improvement in corrosion resistance in the
Fig. 7. Optical microscopy images of aluminum samples after ZRA tests between CFRP and aluminum: (a) 16 h; (b) 60 h. The arrows indicate corrosion pits.

Fig. 8. Measurements of current density between drawn aluminum wire and the CFRP with (a) phenolic resin, (b) epoxy resin, and (c) epoxy resin/polyester braiding. The average galvanic currents are presented in (d).

Fig. 9. Scanning electron microscopy images of the CFRP, showing the phenolic resin matrix and raw fibers.
presence of the organic inhibitor. Tavakkolizadeh and Saadatem- anesh [14], for example, estimated the corrosion rate of the steel when coupled with the carbon in seawater solution using the Evan diagram and galvanic corrosion measurements. The authors reported a corrosion rate of 227 $\mu$A cm$^{-2}$ and 85 $\mu$A cm$^{-2}$ by Evan diagram and galvanic corrosion measurements, respectively. When they applied a thin epoxy coating, it was reported a decrease of corrosion rate to 18 e 8.5 $\mu$A cm$^{-2}$ for epoxy thickness of 0.25 and 0.10 mm using galvanic corrosion measurements, respectively. The authors highlighted an improvement of corrosion resistance of the coupled system with epoxy coating.

Among the systems analyzed, the CFRP with epoxy-based resin and polyester braiding showed the best corrosion resistance. There was no current between the two electrodes (Fig. 8c); the magnitude of the current was of the same order as the instrumental noise. Fig. 8d shows the large differences in the average galvanic currents obtained for the three coatings. Fig. 11 shows the integrity of the coating, no defect is highlighted.

Measurements of sample cross-sections were performed using optical microscopy. The fibers produced using phenolic resin, epoxy resin, and epoxy resin with braiding showed thicknesses of 50 ± 6, 21 ± 1, and 53 ± 4 $\mu$m, respectively. A dark field optical microscopy image of the CFRP sample with phenolic resin coating is shown in Fig. 12. Although it was anticipated that a thicker coating would provide a more effective physical barrier, hence decreasing the possibility of galvanic corrosion, the presence of raw fibers was observed for the samples produced with phenolic resin. Consequently, direct contact between the aluminum and the raw carbon fibers favored the occurrence of galvanic coupling. Despite the thinner coating, the combination of epoxy coating and braiding provided effective avoidance of direct contact between...
the aluminum and the carbon fibers, hence preventing galvanic coupling.

3.2. Thermal performance of the pultruded samples

The results of the TGA analyses of the CFRP with epoxy-based and phenol formaldehyde resins are shown in Fig. 13. The thermal decomposition of the epoxy resin system began at 300 °C (onset temperature), with subsequent rapid decomposition in a single step (Fig. 13a). In the final phase of the process, about 83% of the mass remained (approximately the carbon fiber content of the composite). The decomposition of the phenol formaldehyde resin system occurred at a slower rate, compared to the epoxy system, indicating that the system was thermally more stable. The decomposition process started at 320 °C and occurred in at least two steps (Fig. 13b). The remaining residue was equivalent to about 87% of the initial mass and corresponded mainly to the carbon fiber content.

The results of the DMA analyses of the CFRP with phenol formaldehyde and epoxy-based resins are shown in Fig. 14 and Fig. 15, respectively. The tan δ plots indicated that the glass transition temperatures ($T_g$) of the composites were 154 and 124 °C for the phenol formaldehyde and epoxy matrices, respectively. The $T_g$ is the temperature at which the polymer shows a significant increase in mobility, and can be directly related to the working temperature of the final composite, because above the $T_g$ the mechanical properties of the composite become compromised and creep increases. Therefore, initial comparison of the composites suggested that the phenol formaldehyde resin system should provide better performance at higher temperatures. However, the epoxy-based resin was developed for post-cure processes. The DMA test was therefore repeated nine months after fabrication, under room temperature conditions, in order to determine whether the post-cure process occurred at room temperature, and what effect it might have on $T_g$. The tan δ plot temperature was 141 °C, which was
similar to the temperature obtained for the phenol formaldehyde resin composite, showing that the working temperatures of these materials were not significantly different. (See Fig. 15)

Another consideration is that an increase in $T_g$ can also occur under field conditions, where ACCC cables are constantly heated by the Joule effect, which can itself increase the working temperature and extend the cable lifetime. A DSC measurement was therefore made of the epoxy-based resin system after post-curing for 12 h at 180 °C. The $T_g$ value obtained was 200.7 °C (Fig. 16), indicating that it should be possible to achieve higher $T_g$ values using optimized curing procedures.

It is important to point out that environmental exposure can also affect $T_g$ depending on the polymer system and the bonding. Bound water can act as a plasticizer and lower the $T_g$ of the initial inter-chain van der Waals’ forces and hydrogen bonds resulting in increased chain segment mobility. In contrast, bound water can lessen the extent of $T_g$ depression in water-saturated materials, due to secondary cross-linking. Zhou and Lucas [35] evaluated the influence of hygrothermal effects on the $T_g$ of epoxy systems and found that changes in $T_g$ did not solely depend on the water content alone, but were also influenced by the hygrothermal history of the material. Longer times and higher exposure temperatures resulted in higher $T_g$ values. It is therefore important to consider the influence of environmental exposure on the $T_g$ value of the system, in order to be able to predict the maximum working temperature of the conductor cables.

4. Conclusions

Two configurations (Raven and Linnet) are proposed for ACCC cables. In conventional ACSR cables, the steel core is in contact with drawn aluminum. The replacement of the steel core by a composite core means that galvanic corrosion between the carbon fiber composite and the aluminum becomes a concern. Three different coatings were therefore evaluated in terms of their ability to prevent galvanic corrosion between the composite and the aluminum wires. Coatings using epoxy resin and epoxy resin with polyester braiding were shown to be effective in preventing galvanic currents, with the latter eliminating the galvanic current. In contrast, a phenol formaldehyde resin coating was unable to prevent the galvanic current, due to direct contact of the raw carbon fibers with the aluminum.

It is important to consider the thermal stability of ACCC cables. The polymers used in composite cores should be resistant up to 200 °C, which is the working temperature during periods of high demand. The phenol formaldehyde resin system showed a higher glass transition temperature and greater thermal stability, compared to the epoxy-based system. On the other hand, the epoxy resin system could achieve higher glass transition temperatures of up to 200 °C following post-curing. This, together with a greater level of protection against corrosion, makes the epoxy system suitable for use in ACCC cables.

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