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Silicone insulators of power transmission lines with a variable inorganic load concentration: Electrical and physiochemical analyses

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ABSTRACT

Polymeric insulation is an increasing tendency in projects and maintenance of electrical networks for power distribution and transmission. Electrical power devices (e.g., insulators and surge arresters) developed by using polymeric insulation presents many advantages compared to the prior power components using ceramic insulation, such as: a better performance under high pollution environment; high hydrophobicity; high resistance to mechanical, electrical and chemical stresses. The practice with silicone insulators in polluted environments has shown that the ideal performance is directly related to insulator design and polymer formulation. One of the most common misunderstandings in the design of silicone compounds for insulators is the amount of inorganic load used in their formulation. This paper attempts to clarify how the variation of the inorganic load amount affects physicochemical characteristics of different silicone compounds. The physicochemical evaluation is performed from several measurements, such as: density, hardness, elongation, tensile strength. In addition, the evaluation of the physicochemical structure is carried out using infrared test and scanning electronic microscopy (SEM). The electrical analysis is performed from the electric tracking wheel and erosion test, in agreement with the recommendation of the International Electrotechnical Commission (IEC).

1. Introduction

In the past thirty years, glass and porcelain insulators have been substituted by a relatively new class of insulator composed of polymeric compounds [1]. This technology has been used in distribution and transmission systems. The first transmission line with composite insulators was installed in Germany in 1969 [2]. Currently, the polymer insulators represent more than 40% of the new insulation market in the United States [3].

In Brazil, the replacement of ceramic to polymer insulators began in 1987, because of the limited experience on the electrical performance of these polymeric compounds as function of the aging and physicochemical degradation caused by environmental agents [3,4]. However, currently, there is more than 50,000 km of transmission and distribution overhead lines, corresponding approximately to 400,000 new insulators [5].

Silicone, Terpolymer Ethylene and Propylene Diene (EPDM) are materials used in the manufacturing of great part of the polymeric insulators. However, the use of silicone in the insulator housing has increased in the last few years even more, mainly because of the great performance in the hydrophobicity recovery [2,3,6,7].

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The analysis of the insulation coordination for overhead transmission lines is not a trivial task. Specific issues related to the environment characteristics, weather and pollution should be taken into account. In regions with high pollution levels, silicone insulators are more appropriate (and also more expensive) than their similar-based EPDM. The silicone insulators are also more appropriate in areas with specific climatic conditions, e.g., sea coast locations and tropical weather conditions [3].

The adequate physicochemical formulation, based on polymer and other components, combined with an optimized physical structure of the insulator body can significantly improve the insulation levels of transmission and distribution networks. The variation in the polymeric housing formulation results in 20% up to 80% on the weight of the material. Some additives included in the polymeric housing of insulators reduce manufacturer costs, facilitate the processing of materials and also improve the performance of these insulators [1,3].

Some studies have been conducted to evaluate the aging and degradation process on polymeric insulators, in order to establish standards for aging/degradation tests in a reduced-time scale. The aging/degradation tests on polymeric devices are possible by means of an environment with temperature, moisture and pollution controlled, in order to induce an accelerated aging and degradation on the samples [3,8,9]. Based on the technical literature, the degradation caused by aging is responsible for approximately 65% of failures in polymeric insulators. This means that the remaining 35% are caused from mechanical and electrical stresses [3,4].

One of the most classical tests for assessing the performance of insulators on severe environmental conditions and polluted areas is expensive and long, i.e., approximately 5000 h [10]. However, a new test was proposed in 2004, recommended by the IEC 62217 [11], representing a test procedure less expensive and faster than the prior procedure with 5000 h. This test is known as roll of electrical routing or electric tracking wheel.

The roll of electrical routing is a relatively new test, which allows to compare the performance of different insulators keeping the same material or to evaluate different polymeric compounds keeping the same project.

This paper proposes a complete investigation of silicone compounds with different concentrations of inorganic loads using the roll of electrical routing. Physiochemical measurements were carried out to evaluate several electrical and mechanical variations among the silicone compounds. Therefore, results and conclusions presented from the test procedure proposed in this paper represent a great database and reference for further researches and manufacturing processes of polymeric insulators.

2. Silicone insulators

The silicone rubber compounds evaluated in the proposed study are five types, varying according to the inorganic load concentration:

1. (S1) – silicone rubber compound with HTV (High Temperature Vulcanizing) fumed Silica and Alumina Trihydrate (ATH) zero parts.
2. (S2) – S1 + 25 parties of fumed silica and ATH.
3. (S3) – S1 + 50 parties of fumed silica and ATH.
4. (S4) – S1 + 75 parties of fumed silica and ATH.
5. (S5) – S1 + 100 parties of fumed silica and ATH.

The compounds used in this research were manufactured by Bluestar Silicones Brasil Ltda.

3. Electric tracking wheel

The IEC 62217 describes two or four insulators characterized by the same compound with creepage distance between 500 mm and 800 mm, which are tested simultaneously in the stem routing. Before starting the test, insulators are cleaned with deionized water. In sequence, the samples are arranges in four positions, as illustrated in Fig. 1. The rotation process consists in each sample stays stopped around 40 s at each position. Each 90° rotation step takes approximately 8 s [11].

The first step of the cycle (Immersion Time, as described in Fig. 1), the sample is immersed in a saline solution. The following step (Following Time, in Fig. 1), the sample receives an excess of saline flow, ensuring that slight moisture on the surface induces discharges through the dry bands formed in the third step. The Energized Time or third step, the sample is energized with industrial-frequency voltage for 40 s. In the last step (Cooling Time, in Fig. 1), the sample is cooled after the overheating, resulted from the surface discharges in the Energized Time.

Through the test procedure, the saline solution was replaced during the weekly interruptions for inspection. These interruptions along the test time did not spend more

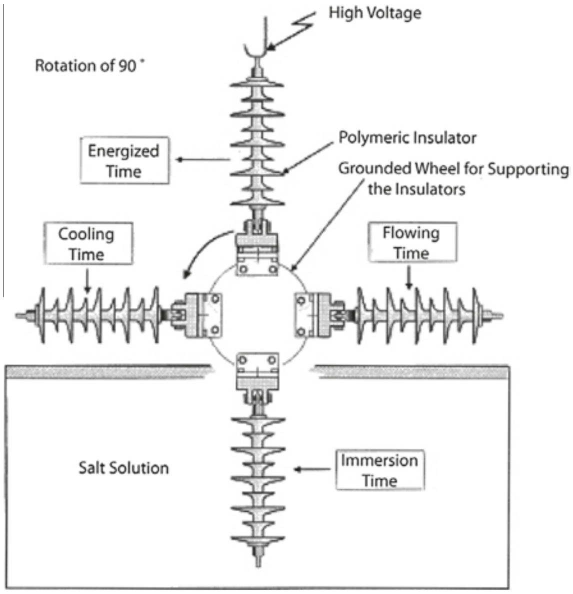

Fig. 1. Schematic illustration of the electric tracking wheel.

than one hour. Interruption periods were not computed in the total time of test.

The voltage considered in the electrical test was set by dividing the leakage distance measure in the insulator by 28.6 mm. The concentration of NaCl in deionized water was 2.80 kg/m^3 ± 0.06 kg/m^3. The chamber temperature was set as 20 ± 5 °C and the total duration of the test was 15,000 cycles (800 h). The IEC 62217 determines that the amount of NaCl for the saline solution must be 1.4 kg/m^3 and duration of the trial should be 30,000 cycles [11]. However, the proposed test was carried out with half of cycles suggested by the IEC and the concentration of NaCl in water was two times major than suggested by the norms. There are no standard correlations between the techniques presented in IEC 62217 and the proposed procedure; however, the results and measurements obtained in this research are in agreement with those obtained following the norms.

The conclusions obtained from this research were based on measurements of density, hardness, elongation and tensile of the silicone compounds of the insulators. The electric tracking and erosion test, infrared and scanning electronic microscopy raised several issues related to the physiochemical degradation of the silicone compounds.

4. Results and discussions

In this section, the methodology adopted for each test procedure and following measurements are discussed separately as well as the evaluation criteria for each measurement.

4.1. Wheel of electric tracking

One way to assess electric tracking in an insulator is to submit it to a number of cycles to failure (Table 1). It is assumed in this test that the device will not fail until the end of the total 15,000 cycles. However, the methodology of the IEC 62217 is not totally suitable to the proposed test, considering the number of cycles, NaCl concentration and also that the IEC standard is recommended for commercial materials, which is not the case of the silicone compounds studied in this research.

Table 1 shows the number of cycles before failure of each insulator sample (1–4) and the average of number of cycles for each compound (S1–S5).

Best electrical performances were observed for the compounds with a major concentration of ATH, as observed in the average obtained from the number of cycles of each compound, in Table 1. Otherwise, the worse performance was observed for the insulators manufactured using the compound S1, without ATH.

Table 1
Electric tracking cycles per insulator sample and per compound (S1–S5).

	1	2	3	4	Avg.
S1	5600	4327	6498	6498	5730
S2	5351	15,009	10,370	7250	9495
S3	9230	12,288	12,288	5532	9834
S4	10,350	16,531	10,350	11,060	12,070
S5	13,353	13,353	11,670	13,353	12,930

4.2. Density

The test to determine the density was carried out in triples. The mass and volume of three pycnometers were measured in an analytical balance, using thermometer and deionized water. In each pycnometer was introduced 20 g of well minced silicone rubber and the pycnometer volume was filled with a liquid of well-defined density. The microair bubbles in the material were removed with a vacuum pump and a dessicator for few hours.

In sequence, the pycnometer volume was again adjusted with the same liquid and the temperature of the system was fixed at 25 °C. After that, the total mass of the pycnometer filled with rubber and fluid was measured again. Thus, calculating the difference in the masses of pycnometer with rubber and vacuum and the pycnometer with rubber and fluid, the bulk density of the liquid leads precisely to the rubber density.

Therefore, based on the given measurement process, Fig. 2 shows the density values of the silicone compounds S1–S5.

Fig. 2 shows that the bulk densities increase with the major concentration of loads in the silicone compounds.

The behavior observed in Fig. 2 was expected taken into account that the ATH density is major than the Polydimethylsiloxane (PDMS) which is the main constituent the silicone rubber. Thus, it is natural that increasing the amount of denser material in the compound, the bulk density of the material will be major as well.

4.3. Hardness

The hardness measures were obtained with a durometer type Shore A, model Kori KR 14A in triplicate. The specimens were 6 mm thick and vulcanized at 180 °C for 10 min.

Fig. 3 shows the results of Shore A hardness test for silicone compounds with different ATH quantities.

These results indicate that major quantities of load in the compound results in major values of hardness. This behavior was expected for polymer composites. However, this measurement shows the exact value of the hardness

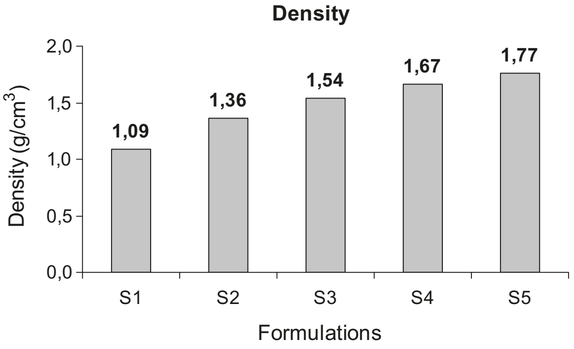

Fig. 2. Roughening scheme of the specimens of the sub stage II-D.

for the specific compounds given by S1–S5, according to the amount of ATH in the formulations.

4.4. Maximum elongation and tensile strength

These tests were conducted under recommendations of the ASTM D 412 standard [12]. The test specimens were molded with 2 mm thick and vulcanized at 180 °C for a period of 10 min.

Seven specimens were obtained using "Die C" form according to the standard [12]; after that, they were tested in a universal testing machine Kratos, model K2001. The load cell used in the test was 200 kgf and the speed was 500 mm/min.

To register very low elongation values, a strength gage produced by Kratos was used.

The elongation of silicone compounds with different loads is presented in Fig. 4. It is observed that the elongation varies inversely to the amount of filler in the composite. The interaction of filler with the rubber produces a largest hardness, on the other hand, the same interaction difficult the molecule rubber elongation.

Another important mechanical property of polymer composites is their tensile strength. These measurements are presented in Fig. 5.

From the results in Fig. 5, the tensile measurements for the five compounds did not show a linear behavior, as observed in the prior analyses. A better performance was observer for the specimen S2, with 25 parties of fumed silica and ATH. The tensile strength performances of S3–S5 decrease with the increase of amount of silica and ATH.

Another observation is that the results of tensile strength are inversely proportional to the hardness measurements presented in Fig. 3. This means that with a greater hardness, the compound presents a minor rupture tensile strength.

4.5. Tear resistance

This trial was conducted under recommendations of the ASTM D 624 standards [13]. The test specimens were molded with 2 mm thick and vulcanized at 180 °C for a period of 10 min, such as for the elongation and tensile tests.

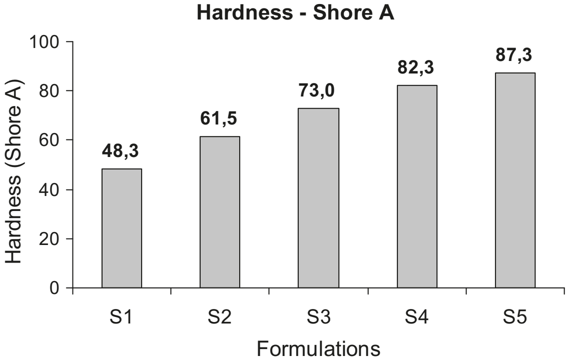

Fig. 3. Shore A hardness of rubber with different ATH concentrations.

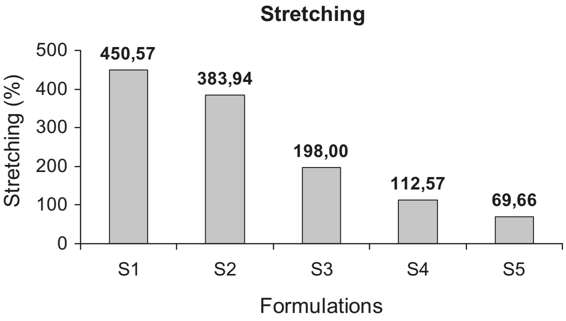

Fig. 4. Maximum elongation of silicone rubbers with different ATH concentrations.

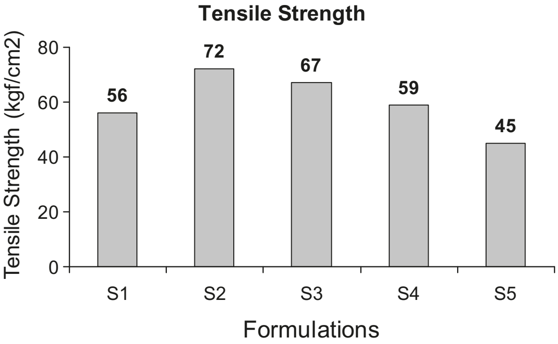

Fig. 5. Tensile strength variation with ATH filler concentration for composites rubber based.

Seven specimens were obtained using "Die C" form according to the ASTM D 624 standards and tested using a machine testing mechanical Kratos model K200, based on the same conditions described in the elongation.

The tear resistance is one of the most important properties of the composites in insulators. Fig. 6 shows the behavior of tear depending of the ATH amount in the compounds. Similarly to the maximum elongation behavior (Fig. 4), the tear resistance decreases with major concentrations of ATH in the compound formulation.

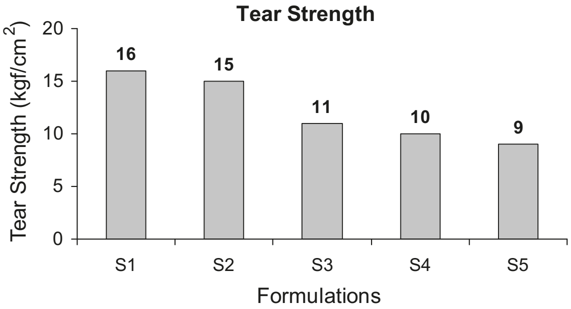

Fig. 6. Tear resistance of rubbers with different ATH concentrations.

4.6. Electrical tracking and erosion

The equipment used for this test was manufactured by Balestro Ltda. The specimens were 6 mm thick and were vulcanized at 180 °C for a period of 10 min.

The specimens were sanded and tested according to NBR 10296 standards [9].

The pollutant solution, with a resistivity of 4.05 Ω m, was prepared at a concentration of 0.1% of Ammonium Chloride (NH_4Cl) and 0.02% of wetting agent Isooctil Phenoxypolietoxietanol.

The test started with a tension of 1 kV and was increased 0.25 kV per hour [9]. The weights of the specimens were measured before and after tests.

The trials of electrical routing and short period of erosion in inclined plane provided many details regarding the formulations studied in this work. The voltage values for each compound *versus* the respective electrical routing resistances are described in Fig. 7.

The results show that the increase of the ATH concentration is proportional to the increase of the resistance of electrical tracking. These results were previously observed in reference [3]. The difference between this work was the reference based on the NBR 10296 [9], whereas reference [3] adopted the standards presented in ASTM 2303[14]. However, in fact, the NBR 10296 and ASTM D 2303 are practically similar.

In Fig. 8, the maximum and minimum values show a major variation for the compound S3, while the more homogeneous result was verified for the compound S5.

Fig. 9 shows the mass lost average at the maximum and minimum erosion, for each compound. It is possible to verify that the mass lost average is almost close to the average value between the extremes of maximum and minimum, except for the compound S5. The compound S5 showed a deviation of the minimum mass loss, what demonstrates that the mass loss was not similar for the five specimens.

Fig. 10 shows the volume lost by erosion in the electrical tracking test.

According to Fig. 10, the loss of volume by material erosion was similar to the mass loss (Fig. 9). This behavior can be explained from the same arguments to explain the mass loss. These last two results show that only the voltage discharge (when it occurs routing) is not enough for a reliable evaluation of insulator compound. It is more appropriate to combine the electrical tracking and erosion test with other tests for more accurate conclusions, such as the mechanical tests of elongation and tensile strength. However, even so, the volume or/and mass erosion are important parameters for evaluation of silicone compounds.

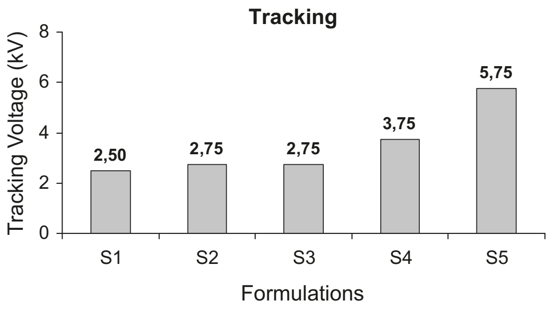

Fig. 7. Values of electrical tracking voltage and erosion according to NBR 10296 standard.

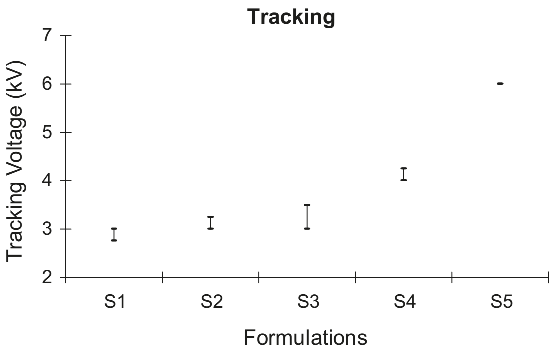

Fig. 8. Minimum and maximum electrical tracking voltage.

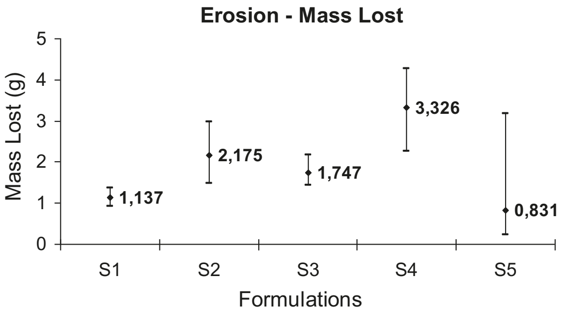

Fig. 9. Mass lost by erosion in the electrical tracking test.

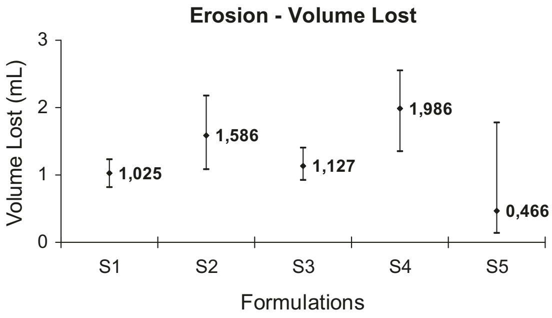

Fig. 10. Volume lost by erosion in the test of electrical tracking.

4.7. Infrared – FTIR

The spectra were carried out using an infrared spectrophotometer Nicolet, model Magna-560, scanning range of 400–4000 cm^{-1} (infrared middle) and resolution of 4 cm^{-1}. The measures were conducted by diffuse reflectance (DRIFT) on the surface of the polymer. The best definition was obtained with 128 scans.

The infrared responses for the five compounds are described in Fig. 11, into the wavenumber range from 4000 to 400 cm^{-1}.

Reference [15] allocated bands composed of silicone observed in commercial insulators. The absorption bands at 2960 cm^{-1} and 1270 cm^{-1} are related to C–H and Si–CH$_3$

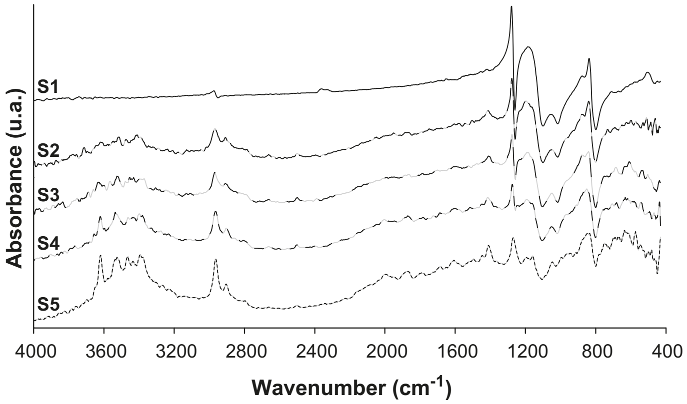

Fig. 11. Infrared spectra of rubbers with different ATH concentrations.

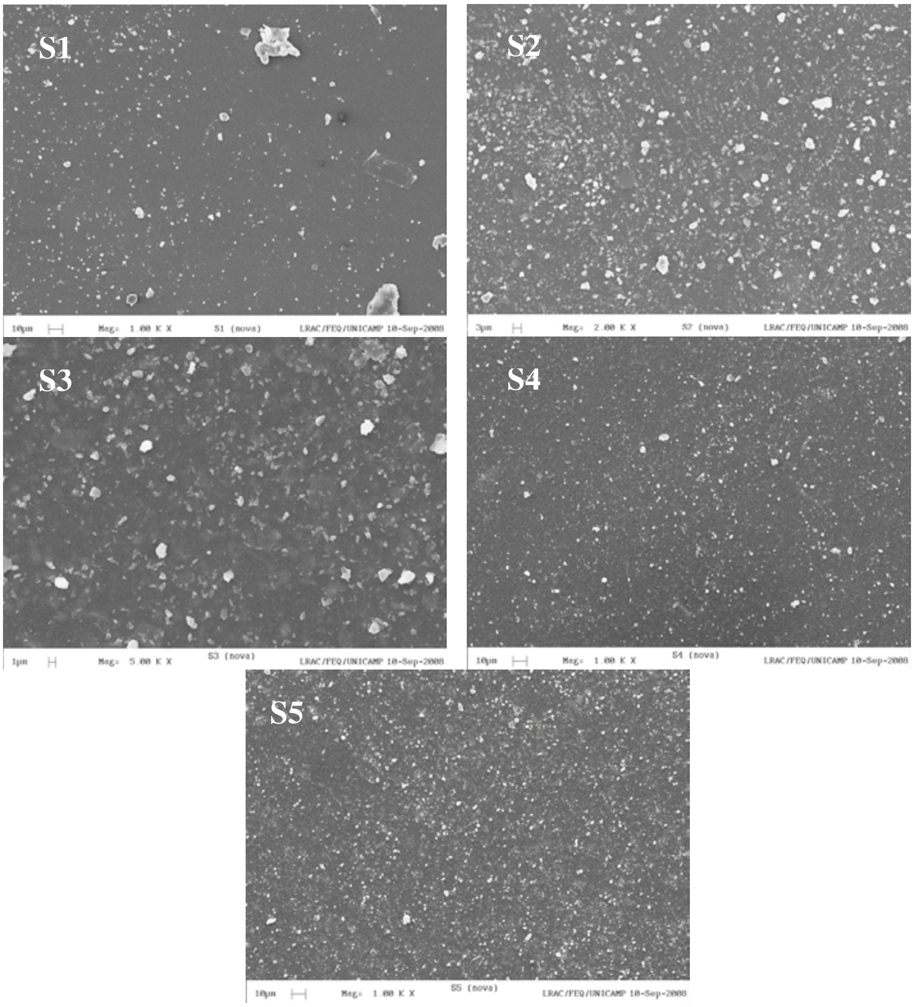

Fig. 12. SEM micrographs of the new insulator compounds surfaces S1–S5 (1000×).

stretching, respectively, which are associated with CH_3 side groups. The absorption band at 1020 cm^{-1} is attributed to the Si–O–Si group of the polymer main chain.

The absorption range between 3700 and 3200 cm^{-1} is related to OH groups, which are associated with the Alumina Trihydrate filler (ATH).

Fig. 11 shows a more intense absorption at 3700 and 3200 cm^{-1}, which means a major concentration of ATH filler in the compound. The absorption bands at 1270 cm^{-1} and 1020 cm^{-1} are more intense in the compound with less ATH filler.

The variations observed around 800 cm^{-1} are associated with the Si–C vibration stretching and CH_3 rocking [15,16].

These results are important because demonstrate a semi-quantitative nature of the infrared technique.

4.8. Scanning electronic microscopy – SEM

The scanning of the compound by electronic microscopy shows several details on the molecular structure of the ATH with the PDMS. Based on this information, the silicone rubber quality can be evaluated as well as the validation of the results obtained from the physiochemical testes presented in the previous sections.

The SEM of the cryogenic fracture is an important procedure to observe the morphology and molecular structure into the insulator compound. Otherwise, only the surface of the specimens could be evaluated, without a proper analysis of the load concentration into the specimens.

The cryogenic fracture process consists to immerse the specimens in liquid nitrogen, which are cooled to the glass transition temperature. Thus, the specimens can be fractured without damages of their internal structure. Otherwise, a fracture or cut at ambient temperature, using a conventional cutting tool, deforms the internal structure of the compound. This means that the load distribution in the polymeric compound will be modified because of the deformation resulted from the mechanical action of the cutting tool, which makes the results obtained from the SEM unreliable.

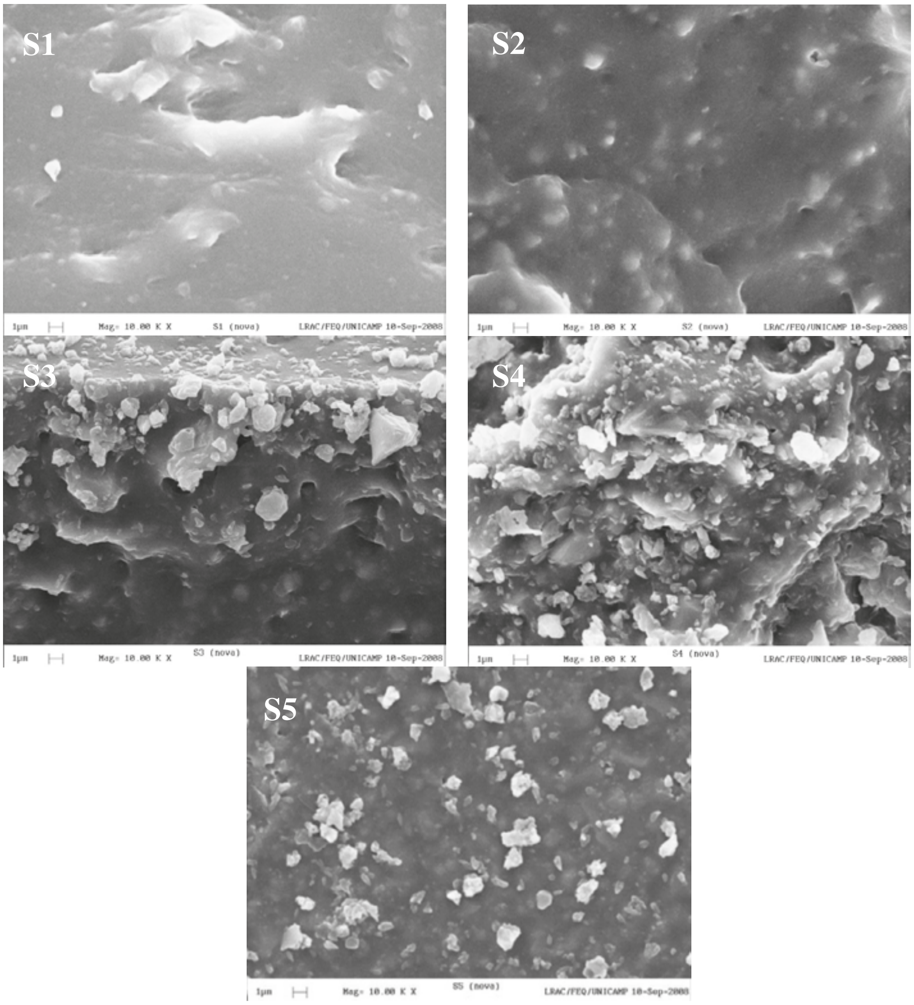

Fig. 13. SEM micrographs of the cryogenic fractures of S1–S5 (1000×).

The morphology of new and aged rubber insulators was tested using a Leica scanning electronic microscope (SEM), model LEO 440i. The top surface and the internal surface (cryogenic fracture) of the specimens were observed and analyzed as follows.

In addition, the specimens were also analyzed using Energy Dispersive Spectroscopy X-ray (EDX) in order to detect other elements on the insulators surfaces.

The micrographs of external and internal surfaces and the EDX spectra are shown in this section.

Fig. 12 shows the micrographs of the surface of new insulators composed of S1–S5, before the aging at the wheel of routing. The micrograins composed of inorganic fillers (white points) are more abundant in compounds formulated with higher concentrations of ATH. The inorganic fillers are also homogeneously distributed on the external surface of the specimens, which proves the good quality in the molding process of the specimens.

Fig. 13 shows the micrographs of the surfaces obtained from the cryogenic fractures of the insulators before aging at the wheel of routing.

The fillers dispersion is more defined in the micrographs in Fig. 13 than in Fig. 12. This dispersion is resulted from the action of the liquid nitrogen on the compound surfaces.

The images, in Figs. 12 and 13, show a major load concentration on the internal surfaces (by cryogenic fracture) than on the external surfaces. This behavior shows that the PDMS tends to involve the load fillers, which results a major load concentration into the silicone-rubber insulators.

Fig. 13 shows that a major load amount results a minor PDMS phase. However, results show that the progressive load increase did not result a saturation or dissolution of the compounds with major load concentrations, even in S4 and S5.

The micrographś surfaces of the compounds S1–S5 after aging by tracking wheel are observed in Fig. 14.

In Fig. 14, the compounds S1, S2 and S5 did not present significant variations on the surface texture. On the other hand, surface textures of S3 and S4 were degraded by action of electrical discharges, which are generated by partial formation of dry bands during the wheel test. Based on these images and other images of S3 and S4, degradation or structural damage were not verified for the five compounds.

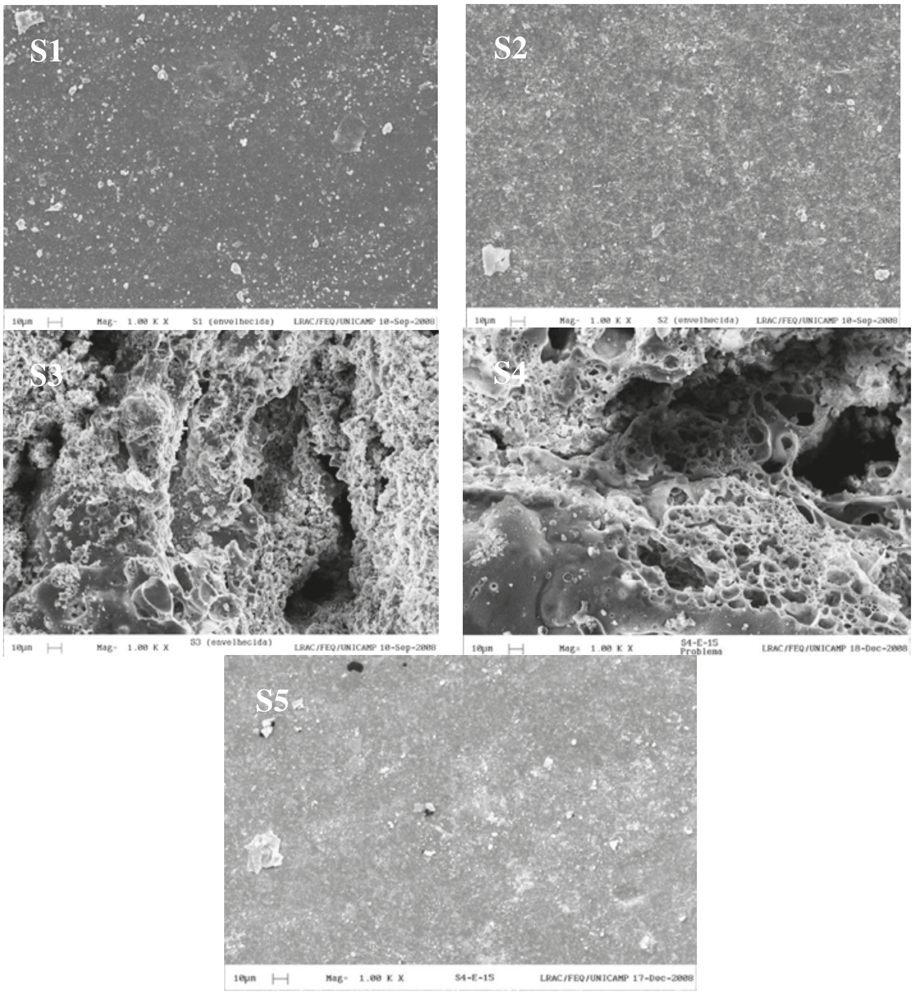

Fig. 14. SEM micrographs of the insulator compounds surfaces S1–S5 after the wheel of electric tracking test (1000×).

The micrographs of the aged surfaces, from the cryogenic fractures, are shown in Fig. 15. The micro-images describe the same behaviors as in Fig. 14, especially for compounds S3–S5. Deep degradation of the polymer matrix was observed, which exposed the inorganic loads of compounds S3, S4 and S5.

In addition, the analyses from the EDX spectrum of new compounds proved a significant amount of Si atoms, as described in Fig. 16.

The EDX spectra of the aging compounds by electric tracking wheel are described in Fig. 17(a) for compound S1 and (b) for S2–S5, with different concentrations of fumed silica and ATH.

The radiation monitoring scale is given in counts per seconds (vertical scale). The horizontal scale is given in keV.

The spectra of the Figs. 16(a) and 17(a) indicates the presence of Si, O, C in the new compound S1. After the wheel test; Si, O, Ca, C, Na and Cl were detected in S1. Thus, the variation between the two spectra is the presence of Na, Ca and Cl atoms which are only observed after the aging procedure. This behavior is attested because of the contamination of the compound by Sodium Chloride in the immersion stage of the wheel process.

The EDX of the compounds S2–S5, before and after the electric tracking wheel test, are shown in Figs. 16(b) and 17(b), respectively. The presence of Al and Ca in the compounds S2–S5 was observed for the new and aged specimens as well, because of the presence of ATH. The same atoms are not present in the compound S1 because there was not ATH in its composition.

In addition, Calcium is not observed in the new compound S1. The presence of Calcium is characteristic in compounds with fillers containing Calcium Carbonate. This means that Ca was not verified in S1 composition, since Calcium Carbonate was not present before the aging process on the compound S1, as described in Fig. 16(a).

By comparing the spectra in Figs. 16(b) and 17(b), after the aging, the contamination by NaCl is expected. Other components, Iron and Zinc (Fe and Zn), were detected from the EDX test. The presence of Fe and Zn can be explained because of the deterioration of the terminal insulators dur-

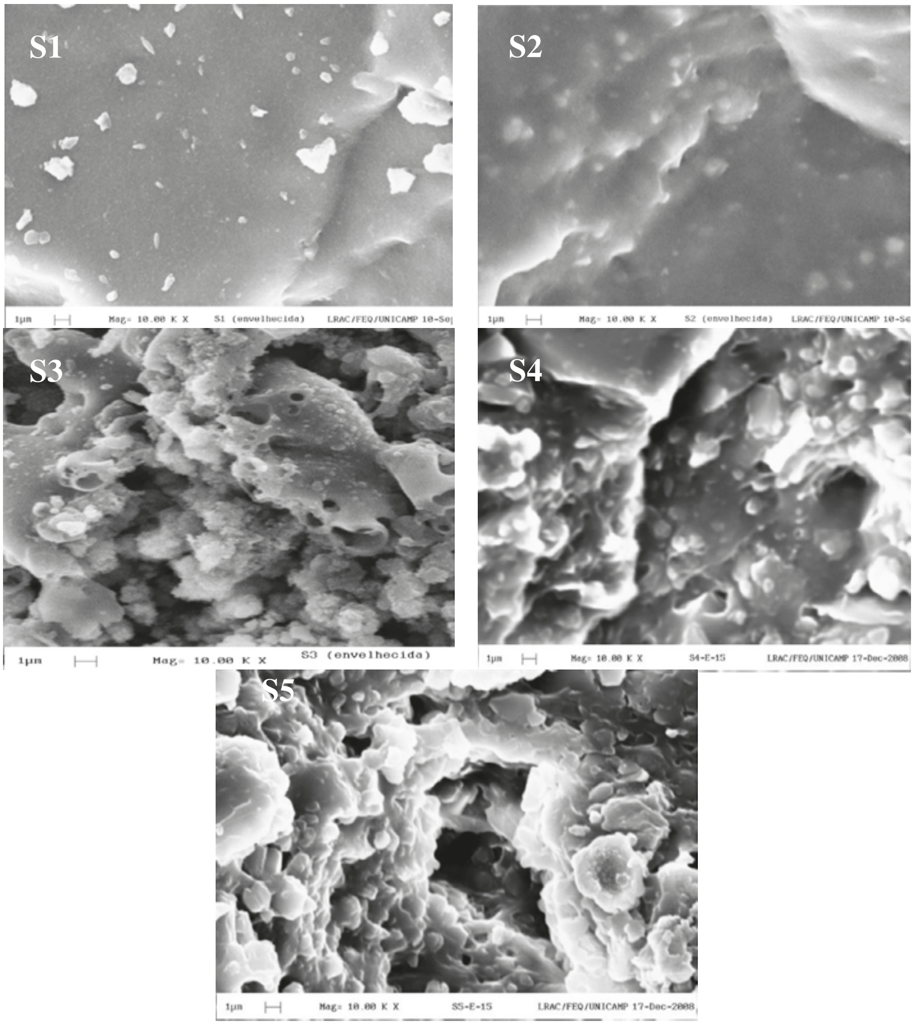

Fig. 15. SEM micrographs of the cryogenic fracture of the aged compounds surfaces S1–S2 after test by electric tracking wheel (1000×).

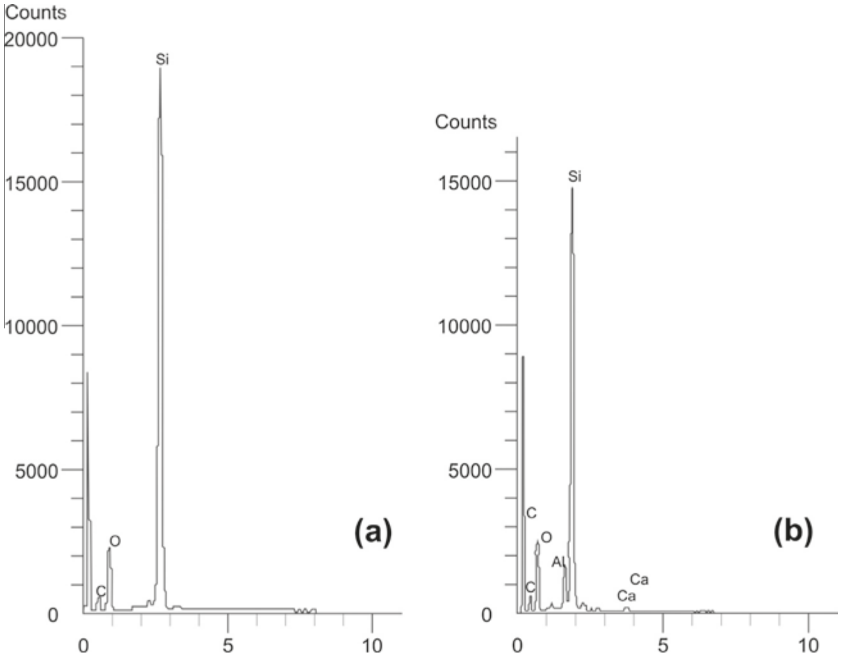

Fig. 16. EDX of the new compound S1 (a). EDX of the new compounds S2, S3, S4 and S5 (b).

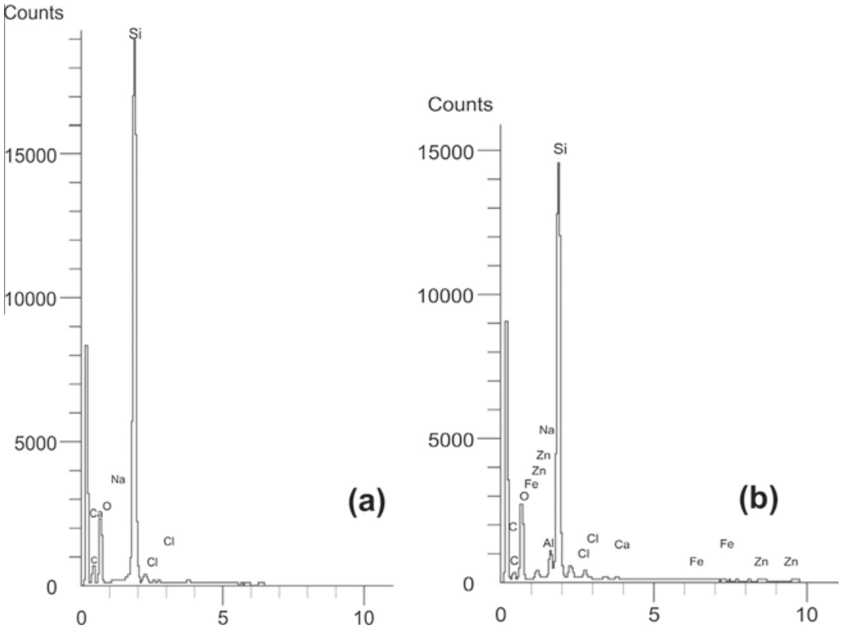

Fig. 17. EDX of the compound S1 (a). EDX of the compounds S2, S3, S4 and S5 (b). After Aging process by electric tracking wheel.

ing the aging process. Zinc came probably from the electroplating and Iron from the steel.

5. Conclusions

From the physiochemical and electrical tests presented in this research, the main conclusions are highlighted as follows:

- The analyses of density, hardness and mechanical tests were efficient to characterize the different compositions of silicone rubber, pointing important details on the quality of the compounds.
- The density is greater for compounds characterized by a major amount of inorganic loads.
- The hardness of the compound is higher with a major concentration of ATH.

- The polymer elongation decreases with major filler concentrations, which means variations on the mechanical properties of the insulator.
- The resistance to tensile shows a nonlinear behavior as function of the filler concentration, as verified for intermediary quantities of fillers, where the major tensile resistances were measured.
- Rip resistance is major for compositions with less filler.
- The infrared test proved to be an efficient technique to determine silicone rubber as well as semi-quantitative technique to determine the amount of ATH fillers.
- The electric tracking test represents an important tool to evaluate polymer compounds for tracking and erosion.
- According to the tracking test, rubber compounds with major load concentrations show better electrical performance than those formulated with less load amounts (Table 1).
- The SEM micrographs of the insulator surfaces and the cryogenic fractures were effective to observe the morphology and degradation regions of the compounds after aging.
- The EDX results showed that this analysis can determine qualitatively the presence of fillers and also the presence of contaminants, such as Sodium Chloride and metals waste from the progressive degradation of the polymer supported by metal accessories during the test.

These conclusions are some of the general observations obtained along the proposed physiochemical and electrical methodology of test. Depending of the insulator design and composition, specific observations and conclusions could slightly differ of the results obtained from the insulators evaluated in this paper. However, the general conclusions on the procedure carried out in this research shows that the use of electromechanical tests associated with the chemical analysis using infrared, EDX and SEM techniques represent an accurate methodology to evaluate the composition of silicone rubber insulators and their electrical performances.

This research presented several specific technical characteristics associated with most of silicone insulators, such as: density, hardness, elongation, mass loss by erosion and many other details that associate these physiochemical prosperities to the load concentration in the compound formulation. However, one of the major contributions presented in this paper is the test methodology for silicone insulators. This methodology associates conclusions obtained from mechanical tests (e.g. density, hardness, elongation, etc.), physiochemical analyses (contamination evaluation using Infrared, EDX tests and SEM images of the microscopic structure of the silicone compounds) and conventional electrical tests, such as the electric tracking and erosion tests. All these test procedures follows the most rigorous standards established by the IEC, the American Society for Testing and Materials – ASTM and the Brazilian Association of Technical Standards ABNT. The combination of these techniques results a complete methodology to evaluate silicone rubber and polymer insulators for research purposes as well as for applications in power distribution and transmission networks.

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