THE BEHAVIOR OF UNDERGROUND POWER CABLES UNDER THE ACTION OF STRESS FACTORS

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The main concern for specialists is to increase the security in electricity supply from electric power stations or electrical transformer posts of the fixed electric installations, by adequate selection of insulating materials, correlating with exploitation conditions from environment and ensured a high resistance at aging of polymeric materials which composing the power cable and this paper will characterize the physicochemical parameters of the exploitation medium of the cable in burial conditions of soil. The premature aging phenomena observed in the case of insulating materials has been explained by induction of manufacturing defects such as air pockets, or the inclusion of certain impurities. Chemical aging is in fact chemical degradation, which is caused by formation of free radicals, which leads to bond breaking or unzipping of the polymer structure. The process can be initiated by thermal or mechanical means, by oxidizing reactions, by hydrolysis, or by UV or ionizing radiation. Polluted environments may cause a direct attack upon a polymer. This has been studied in the context of atmospheric pollution and strong industrial acids/alkalis, but studies applicable to PVC have been limited. For many plastics used in electrical insulation, metals accelerate oxidative pyrolysis. Metallic contaminant inclusions can cause "extreme oxidative degradation", and such metallic contaminants can act to produce initiation sites for electrical treeing. The kinetics of the aging process of insulating materials, direct-buried in different sites, is depending on the physicochemical and microbiological composition of the soil in the specific case sites. Electrical cables used in electricity transmission and distribution of medium and low voltage buried or aerial are materials systems type sandwich which include along with conductor certain materials with insulating role, which assure mechanical and physical-chemical protection.

Key words: power cable, PVC, stress factor, ICP-MS.

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1. INTRODUCTION

Electric cables are very important items in transmission of electric power from generations to consumers. In spite of a wide range of types and dimensions all cables present two main structural elements namely the conductors and the insulations (figure 1). Insulation is a material having good dielectric properties used on wire components in cable usually as direct covering on conductors. It is an important component of the wire. Insulation selection is determined by a number of factors such as stability and long life, dielectric properties, resistance to high temperature, resistance to moisture, mechanical strength and flexibility.

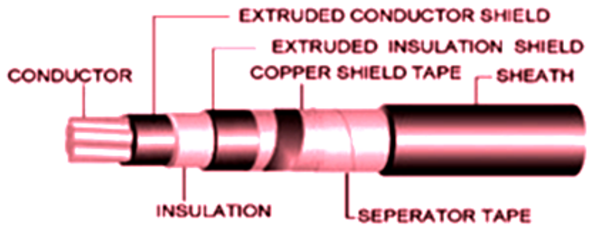


Fig. 1 – The cable structure for electric power transmission from a transformer station to the consumers.

Frequently, the insulation consist in one or more layers of polymer materials, such as XPLE (cross-linked polyethylene), ethylene-propylene copolymer (EPR), ethylene-acetate copolymer (EVA), polyvinyl chloride (PVC) etc. It is very well known that the XPLE has a better electrical performance and is very used as material, comparative with PVC, because has a high resistance to humidity under the influence of electrical stress over a long period [1]. For electrical insulation are used even EPR (ethylene-propylene synthetic rubber) which offers an excellent resistance to heat, oxidation, ozone and aging, abrasion and shock. EPR has a very poor resistance to petroleum oils/fuels, solvents as toluene and trichloroethane [2]. EVA (ethylene-vinyl acetate) is a polymer known as “expanded rubber or foam rubber” approaching elastomers, soft and flexible being processed likes other thermoplastics. EVA material is resistant to humidity having adhesive properties and resistance to UV radiation being used with success for electrical cables [2, 3]. Polyethylene (PE) is a good insulation in terms of electrical properties. It has a low and a stable dielectric constant over all frequencies, a very high insulation resistance and resistance to chemicals and moisture [3]. Chlorosulfonated polyethylene (CSPE) is a thermoset material and known as Hypalon. Adding chloride and sulfonyl groups to polyethylene makes CSPE. This process changes the stiff plastic into a rubbery polymer, which can be cross-linked in many ways. CSPE has excellent mechanical properties such as tear tensile strength and abrasion resistance [4]. Polvinylidene fluorides (PVDF), Kynar, has great mechanical strength, superior resistance to abrasion and cut through and substantially reduced cold-flow which makes it an excellent back plane wire insulation. Kynar is self-extinguishing and radiation resistant. Fluorinated ethylene propylene (FEP) is extrudable in a manner similar to PVC and polyethylene. It has low dielectric constant and is flame and ignition resistant. Also, it is chemically inertness and has a service temperature of 200°C [5-8].

This study show that PVC, the principal resins used as buried cables in electrical insulation, can be degraded by certain factors such as: humidity, the presence of heavy metals, capillarity, osmosis, and the effect of Coulomb forces, dielectrophoresis (DEP), partial discharges, chemical and thermal degradation as well as numerous factors such as external and internal composition. Poly (vinyl chloride) (PVC) is not normally thought of as an environmentally friendly plastic. PVC used for wire/cable insulation, is not used as a pure polymer. The typical wire/cable formulations of insulation contain 52–63% PVC resin, 25–29% plasticizer, around 16% filler (but occasionally as low as 5%), 2–4% stabilizer, 0.2–0.3% wax, and small amounts of lubricants and colorants; occasionally an flame retardants agent is also included. Antioxidants are also often included in small amounts (less than 0.1%). In the case of wire and cable insulation, PVC-based compositions thermally degrade by "zip dechlorohydration". Structural defects in PVC and the presence of oxygen, acids or bases (including HCl itself) both accelerate degradation process of electrical cables [9-11].

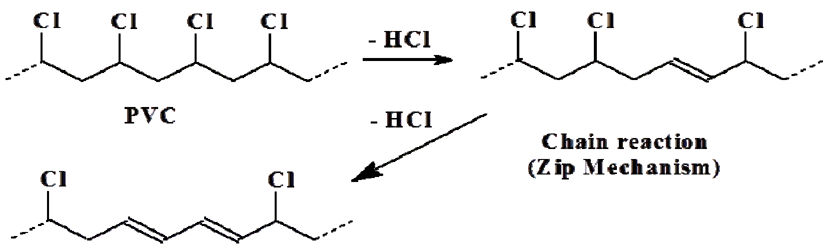


Fig. 2 – Zip dechlorohydration as it occurs during the thermal degradation of poly(vinyl chloride).

The result of the degradation processes is the alteration of the useful properties of the material; this process brings gradual generally named ageing. The factors which decrease the breakdown strength are generally identified as aging or degradation factors and are subdivided into three main categories: electrical aging, physical aging, and chemical aging. For PVC used in electrical insulation, metals accelerate oxidative pyrolysis. Metallic contaminant inclusions can cause "extreme oxidative degradation", and such metallic contaminants can act to produce initiation sites for electrical treeing. The content and proportion of components gives greatly influence soil physical properties, including texture, structure, and porosity, the fraction of pore space in a soil. It is very well known that a normal soil sample is 45 % minerals, 25 % water, 25 % air and 5% organic matter. On the distance between the transformation point (PT) and consumers (being restricted area to use the aerial cable) are used the direct-buried cable. From this point of view can appear some specific problems related to soil characteristics and the nature of stress factors which operates on insulating materials. Problems of buried materials such as: synthetic pesticides and herbicides, petroleum products, organic toxins, heavy metals, are issue to oxidation and this oxidized are increasingly vulnerable to attack by the microorganisms from soil. Humic substances stabilize soil temperatures and water evaporation rate as well as reduce the toxicity of metal cations but don't know studies for the underground power cables.

The soil analysis for medium and low voltage electrical cables will contribute to the monitoring of study strategy of soil contamination with heavy metals and their influence on polymeric insulating material. The analysis and quantification of trace elements including Cu, Pb, Zn, Cr, Cd, Al, Ni, Co, Se in liquid mineralized samples (soil P1-P4, P1'-P4' and initial cable C1-C4 respectively buried cable C1'-C4') was performed by Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) using Perkin Elmer ELAN DRC ICP-MS device.

2. EXPERIMENTAL PART

2.1. SITE DESCRIPTION

Paduchiosu site, from Bucegi Mountain, is refreshing, stimulated and rich in bioclimatic ultraviolet radiation with an enhanced ionization of the atmosphere. The characteristic climate is that of a mountain passage. The average annual temperature is 5-6°C and the abundant precipitations characterizing the last years. In winter it snows plentiful with a decadal average thickness of 15-25 cm in January-February. The average annual atmospheric pressure is 687 mmHg and the dominant wind is from the north and south, persistent on the Paduchiosu Valley.

Samples were collected near of the underground power cable from Bucegi-Paduchiosu area (figure 3) where faults phenomena are frequently, being a rainy zone at high altitude. In this zone the erosion occurs, when the soil is exposed to rain. This phenomenon can disturb the properties of soil by removing the vegetation from the surface of soil and can affect the buried power cables. In many cases is possible that the heavy metal from contaminated soil to migrate on the surface of power cables, which affect during on the period (if one year) the polymeric material of these buried cables. In this respect the global positioning system was used in recording the coordinates and geographical information system (GIS) was used to locate the map of the investigated sites (table 1).

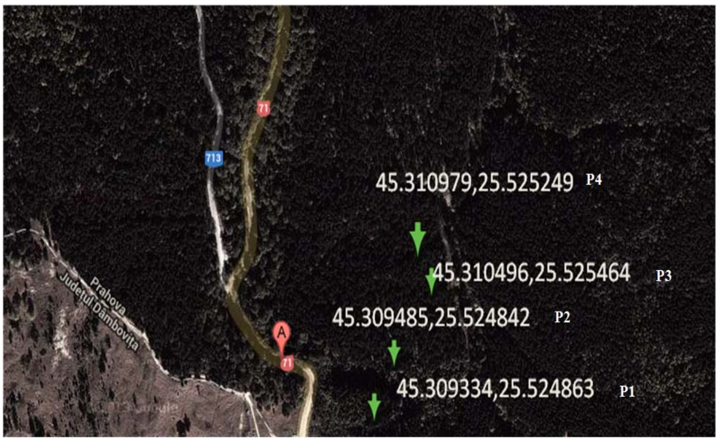


Fig. 3 – Location of sampling points at Paduchiosu site - Bucegi Mountain.

2.2. SAMPLING

The samples (*i.e.* cable and soil) were collected from the vicinity of the buried power cables from Paduchiosu site, near of DN71 (figure 3 and Table 1). Frequently the contamination of mountain soil with heavy metal is governed by several characteristics such as pH, salinity, conductivity and organic matter content of soil as well. All selected samples were collected during the period May 2013–May 2014, after a rainy period, at 45 cm depth, diagonally with buried electric cables.

2.3. INDUCTIVELY COUPLED PLASMA - MASS SPECTROMETRY (ICP-MS) AND SAMPLES PREPARATION PROCEDURES

The concentration level of heavy metals for digestion samples were analysed by using Inductively Coupled Plasma - Mass Spectrometry [16, 17] (*e.g.* Perkin Elmer ELAN DRC ICP-MS device). For all metals analysed, four point calibration procedures were adopted. Calibration solutions for every heavy metal were prepared by serial dilution from a standard stock solution.

In order to ensure that the result were not affected by any interference, concentration of calibration solutions prepared for 9 elements of heavy metal were 10.00 ppm, 1.00 ppm, 0.10 ppm, 0.01 ppm, and 0.00 ppm. In the solution preparation, ultrapure water (18MΩcm resistivity) was used and these calibrations were done using freshly prepared standards.

The Microwave-assisted acid digestion method was used in order to digest the soil and polymer cable samples. A quantity of approximately 0.5 g of soil samples were mineralized with HNO_3 (65% Merck), HCl (37% Aldrich), and

H_2SO_4 (96% Aldrich) according with 3051 EPA standard. Digestion was performed by using a Berghof MWS-2 microwave digester. The digestion was carried out at 220°C, at a pressure of 75 MPa within 55 minute. The filter solutions dilute to 50 mL with the ultra-pure water in a volumetric flask and kept at 4°C in a polyethylene bottle until analysis was conducted [18-20]. To check the analytical precision, randomly chosen samples (about 20% of the total numbers) were measured in triplicate according to International Standard Reference Material: NIST SRM 2709, 2710 and 2711 for soil. All concentrations were reported as mg/kg dry weight of material. Microwave-assisted acid digestion was also used for polymer cable sample digestion using concentrated acids (*i.e.* HNO_3 65% and HCl 37%) according with [21] method.

Soil pH was determined in H_2O and $CaCl_2$ (1:5) according to ISO 10390.2005 (ISO, 2002a). pH determination was performed with Consort 3030 multi-parameter analyser. Conductivity and salinity of extracted soil samples was analysed by using the same device.

3. RESULTS AND DISCUSSION

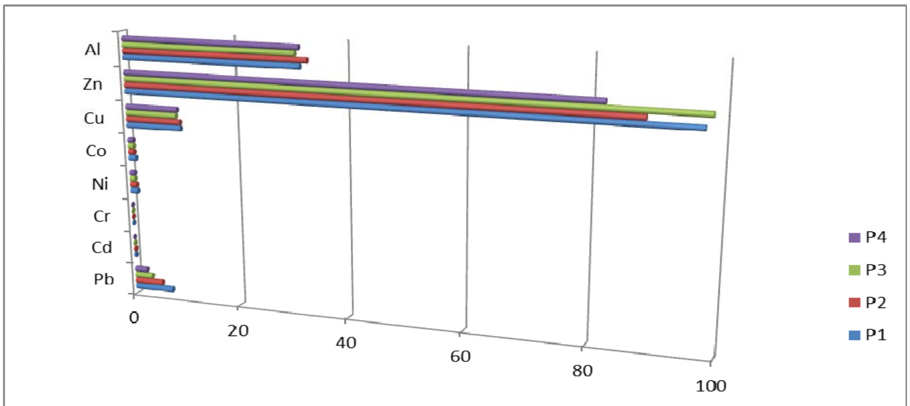
The pH values (moderately acidic) affects the properties of soil. Availability (mobility) of heavy metals from soil is directly dependent on the pH value. The rainfall from this area affects the pH of mountain soil. For this reason, the soil which is formed in high humidity conditions is more acidic than those formed under dry conditions. It is known that acidic soils increase the absorption of metals in plants [22-24] and possible in insulating materials of buried cables. The measured conductivity data of the water-extracted soils indicate the relative small water-soluble salt content of the soil according with data from Table 1.

Table 1

pH, conductivity and salinity of water-extracted soils samples

Soil types	pH	Conductivity [mS]	Salinity [‰]
Braun soil P1	4.8-5.4	8.1	5.2
Braun soil P2	4.91-5.5	8.2	5.3
Braun soil P3	4.95-5.6	8.3	5.2
Braun soil P4	4.85-5.5	8.1	5.3

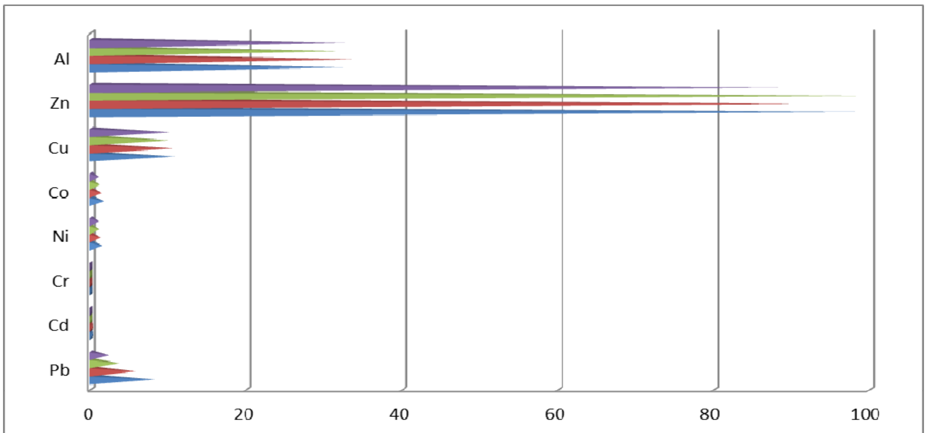
The heavy metals level from soil samples collected in May 2013 is presented in figure 4. Lead content of soils sample collected from the area nearby of the road DN71 (P1 sample) is higher than the content of the samples (P2-P4) collected from 50 m away from the road, in the forest. Generally, cadmium content of soils is below regular value of 1 mg/kg (figure 4).



	Pb	Cd	Cr	Ni	Co	Cu	Zn	Al
P4	2.271	0.092	0.092	0.922	0.987	9.544	82.103	32.092
P3	3.281	0.156	0.089	0.937	1.011	9.321	98.129	31.432
P2	5.014	0.277	0.143	1.176	1.044	10.025	88.204	33.552
P1	7.024	0.287	0.147	1.358	1.335	10.112	97.091	32.251

Fig. 4 – Heavy metal concentrations of soil samples collected in May 2013 [mg/kg].

The heavy metal concentrations of soil samples, collected in May 2014, are presented in figure 5.



	Pb	Cd	Cr	Ni	Co	Cu	Zn	Al
P4'	2.311	0.102	0.109	0.976	0.996	10.102	88.321	32.665
P3'	3.576	0.166	0.103	1.024	1.126	9.943	99.379	31.945
P2'	5.689	0.283	0.158	1.221	1.354	10.643	91.023	33.793
P1'	8.113	0.291	0.159	1.423	1.687	10.765	98.245	32.465

Fig. 5 – Heavy metal concentrations of soil samples collected in May 2014 [mg/kg].

From figure 5 it can see the high level of lead for all soil samples collected from 100 m distance away from the road on buried cable, Paduchiosu area – Bucegi Mountain, in May 2014 comparative with soil samples collected in May 2013. From both figures (*i.e.* figures 4 and 5) it can see highest concentration of lead at site P1 (where metallic contaminant inclusions can cause “extreme oxidative degradation” and produce initiation sites for electrical treeing of the buried cable – frequent are observed cable fault phenomena in the case of insulating materials of the commercial voltage power cable on this area).

The buried electrical installations supports the environmental effects by aerosols, oxygen, particulate matter, nitrogen oxides and sulphur, heavy metals (table 2 and figure 6), by the raining water and other contaminated water, or soil filled with water, substances and microorganisms. The interaction of these factors leads to the tracking and erosion phenomenon, eventually flashover or breakdown. The tracking phenomenon consists by degradation of electrical insulation due to the formation of certain current, which is resulted from the progressive formation of the conductive path, favouring the carbonization of surface. The occurrence of this phenomenon is caused by the presence of: pollution with heavy metals, humidity and pressure. The lifetime of the polymeric insulators depends by environmental local factors and the physicochemical characteristics of the soil, where electric cables are in exploitation. The presence of heavy metals: chromium, nickel, cadmium and lead from the fossil fuel combustion, waste incineration, sludge canalization deposited on the soil and the road traffic can affect the buried electrical cables in exploitation.

Table 2

Heavy metal concentrations in initials and buried power cables collected in May 2013 and 2014 respectively [µg/L]

Electrical cable	Heavy metal concentrations in initials cable [µg/L] on May 2013								
	Pb	Cd	Cr	Ni	Co	Cu	Zn	Al	Se
C1 –C4	0.009 ±0.0002	nd	0.001 ±0.00003	0.005 ±0.0001	nd	0.569 ±0.002	0.017 ±0.0005	nd	nd
Buried electrical cable	Heavy metal concentrations in buried cable [µg/L] on the period of May 2014								
	Pb	Cd	Cr	Ni	Co	Cu	Zn	Al	Se
C1’	0.054 ±0.001	0.006 ±0.0002	0.002 ±0.00008	0.017 ±0.0006	0.039 ±0.001	0.571 ±0.003	0.064 ±0.002	0.068 ±0.003	nd
C2’	0.029 ±0.0007	0.005 ±0.0001	0.001 ±0.00003	0.009 ±0.0003	0.012 ±0.0004	0.575 ±0.004	0.055 ±0.002	0.043 ±0.002	0.001 ±0.00002
C3’	0.023 ±0.0008	0.001 ±0.00005	0.003 ±0.0.0001	0.015 ±0.0004	0.023 ±0.0011	0.570 ±0.003	0.047 ±0.001	0.053 ±0.003	nd
C4’	0.011 ±0.0005	0.001 ±0.00004	0.001 ±0.00005	0.008 ±0.0002	0.019 ±0.0007	0.572 ±0.003	0.041 ±0.001	0.031 ±0.001	nd

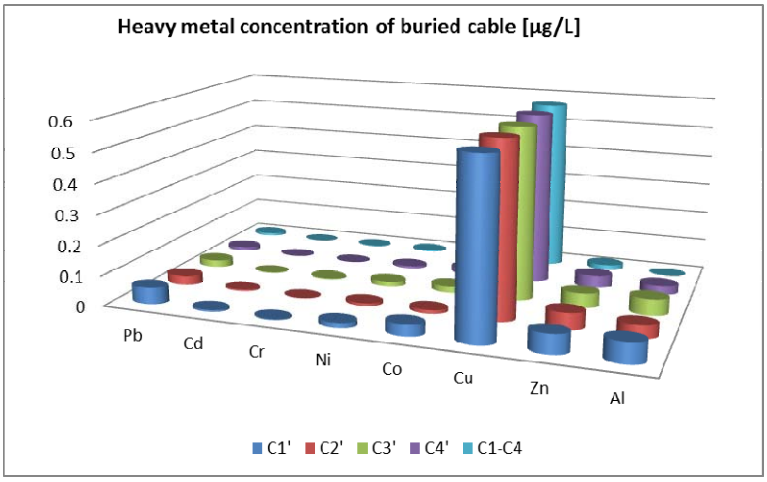


Fig. 6 – Heavy metal concentrations of buried power cable samples collected in May 2014.

4. CONCLUSIONS

The soil analysis for medium and low voltage electrical cables will contribute to the monitoring of study strategy of soil contamination with heavy metals and their influence on polymeric insulating material. Also, it will contribute to the development of knowledge in the field of analytical methods, which will be used to determine certain heavy metals in the soil, before and during the exploitation. This study will contribute, as well at the preparation of the remediation strategy of the electrical cables defects in exploitation according to the contaminated soil with heavy metals. The lifetime of the polymeric insulators depends by environmental local factors and the physicochemical characteristics of the soil, where electric cables are in exploitation. The presence of heavy metals including Pb, Cd, Cr, Ni, Co, Zn, Cu and Al from soil can affect the buried electrical cables in exploitation.

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