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Physical Sciences

Effect of Exposure to Moisture and Petrochemicals on Medium Voltage Cable Jackets

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Abstract. The 15 kV, cross-linked polyethylene (XLPE) insulated underground power cables, having polyethylene (PE) and polyvinyl chloride (PVC) jackets, were studied regarding the influence of moisture, chemicals and petroleum products. PE jackets were found to possess more suitable properties in harsh conditions and performed better than PVC jackets for use in electric power utilities, industry and other uses.

Keywords: petrochemicals, power cables, cable jackets

Introduction

Polymeric insulated power cables are extensively used in transmission and distribution networks around the globe. In Arabian Gulf Cooperation Council (GCC) countries, several manufacturers are producing low, medium and high voltage cables using cross-linked polyethylene (XLPE) insulation and a variety of materials which are mostly installed underground. Cable outer sheaths or jackets provide protection against mechanical damage, ingress of moisture and attacks by ionic species and chemicals etc., present in the sub-surface soil and the underground water. For low-voltage cable, moisture can cause a degradation of electrical properties, such as insulation resistance. In case of instrument/control cables operating at higher frequencies, as well as fiber-optic cables, moisture can cause an increase in the attenuation, resulting in a loss of signal strength, whereas in case of medium and high voltage cables, moisture can lead to insulation degradation due to the water treeing mechanism (Abdolall, 1987; Mashikian and Groeger, 1987; Silver and Lukac, 1984).

In many petrochemical plants and other industrial installations, cables must survive the very corrosive chemical environment. Chemical contamination of soils can also have an adverse effect on the materials used for cables. Oils and organics can swell and deteriorate insulating and jacketing materials, thereby affecting their electrical and physical properties. Inorganics and ions from the soil can migrate into the insulation, leading to poor electrical properties and acceleration of the water tree degradation mechanism. Neutral conductor can be corroded which can increase the electrical resistance. With spiral or helically applied shields, it can result in partial or complete loss of electrical conductivity of the shield (Barras *et al.*, 1997; Graham and Szaniszlo, 1995; Gucwa, 1978).

Mechanical damage of sheath can expose the cable insulation to the environment resulting in rapid deterioration of its properties. Thus a cable sheath must provide resistance to damage before, during and after installation of the cable. Due to these reasons, important factor in achieving optimum cable performance is the careful selection of jacket material (Barras *et al.* 1997). Correlating the intended operating environment and installation conditions of the cable with the attributes of the jacket materials will help maximize its effectiveness.

Several types of cable jackets are currently being used. Polyethylene (PE) jackets are often applied on power cables by electrical utilities and other industrial users. In addition, jackets of polyvinyl chloride (PVC) or chlorinated polyethylene (CPE) are used for cables, as well. CPE compares favourably with PE jacketing compounds, in most of the critical performance parameters. Table 1 illustrates the impact of some chemicals on PE, PVC and CPE sheathing materials (Bayer *et al.*, 1995). Cable jackets in Arabian Gulf region are laid in a geographical terrain where the solar radiation is one of the highest. The subsoil surface elsewhere is marred with high content of chlorides and sulphates while the industrial areas are contaminated with spillovers of hydrocarbon fuels and chemical species. Cable jackets act as the first defense against the impact and permeation of these degradation parameters. Therefore, it is important to study the effects of chemicals and petroleum products on the performance of PE and PVC jackets.

In this research work, medium voltage cables having PE and PVC jackets were buried in soil and exposed to chemicals (NaCl and $CuSO_4$) and petroleum products such as petrol and

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Table 1. Chemical resistance of various sheathing materials (Bayer *et al.*, 1997)

Chemical used (Exposure for 30 days at room temperature)	Rating PE	 PVC
Sulphuric acid (30%)	E	G
Nitric acid (10%)	G	G
Hydrochloric acid (10%)	E	E
Sodium hydroxide (10%)	E	E
Diesel fuel	—	P
Gasoline (regular)	D-P	P
Kerosene	D-P	E
Acetone	G-E	D
Benzene	D-P	P
Transformer oil	—	G

E = Excellent; G = Good; P = Poor; D = Not recommended.

diesel. The effects of these species on important properties of jacket materials were investigated. Moreover, long term performance of medium voltage cables using these two jacket materials were studied under accelerated aging test commonly known as accelerated water treeing test (AWTT) as per AEIC-CS5(1994) to evaluate the penetration effect of water through these jackets to the insulation (Fig. 1).

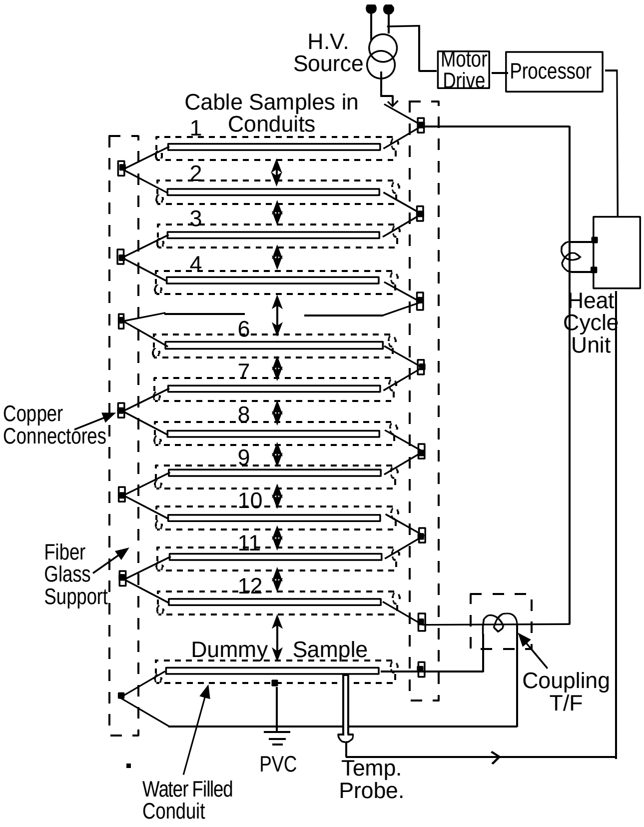


Fig. 1. Accelerated water tree test (AWTT) set up for long term aging of XLPE cables.

Materials and Methods

Medium voltage 15 kV rated power cables are manufactured in GCC countries with PVC and PE sheaths.

The test cables selected for this investigation had conductor cross-section of 50 mm^2 copper (conductor diameter $\approx$ 8.1 mm), bonded semiconducting inner shield of 0.8 mm thickness, XLPE insulation of 4.5 mm thickness and strippable semiconducting insulation shield of 0.8 mm thickness. Metal screen was composed of copper wire plus helically applied copper tape of 16 mm^2 cross-section. However, a reduced thickness of outer sheath (1 mm) was used in order to allow water permeation through the sheath during the accelerated aging. Overall diameter of tested cable samples was ~25 mm. Tests carried out consisted of three parts:

(i) Cables were subjected to AWTT aging by placing cable samples in deionized water filled conduits. (Al-Arainy *et al.*, 2007). Cable conductor was also exposed to water. Cables were arranged in a loop and current was induced in cable conductor to heat it to maximum allowable temperature of 90 °C. During each 24 h period, heating was conducted for 8 h and suspended for 16 h. Simultaneously, cable was stressed with 60 Hz, AC voltage of 3U$_o$ where U$_o$ = rated line to neutral voltage of the cable. This set up is shown in Fig. 1. After aging for 510 days in this manner, the retained dielectric strength (E$_r$) of test cables were measured using high voltage time test method as specified in AEIC-CS5(1994) and were compared with dielectric strength (E$_b$) of new cables.

(ii) To check the effect of $CuSO_4$ and NaCl, cable samples were buried in backfill material in 12 cm diameter plastic pipes. Aqueous ionic solutions of 0.1 molarity were prepared and poured in the plastic pipes containing cables embedded in the middle of the backfill soil and subjected to aging for 39 and 61 days.

(iii) To study the effect of petroleum products, four stainless steel tanks of size 15 cm × 15 cm × 150 cm were used. These were filled with backfill material and the cable samples were buried therein. Then diesel oil and petrol were poured on the backfill material till saturated. The tanks were then covered with plastic sheets to contain their evaporation loss and subjected to aging for 39 and 61 days.

After completion of aging in steps (ii) and (iii) above, jackets were removed and tested for mechanical properties i.e. tensile strength and elongation at break. PVC jackets were additionally subjected to loss of mass test, as well. All jacket samples were subjected also to surface analysis using scanning electron microscope and EDX spectroscopy.

For mechanical properties of new and aged samples, dumbbell test samples were prepared as per IEC-60840(2003). For this purpose universal tensile test machine type Zwick 7050, Germany, was used. A head speed of 25 mm/min was applied.

Measurement of loss of mass was carried out on PVC sheaths to determine the behaviour of the material regarding loss of mass when aged in an air oven, before and after its exposure to petroleum and chemical products. This test was also carried out as per the procedures specified in IEC-60840(2003). Surface morphology and XDF analysis of samples can be used for monitoring and quantifying degradation of polymer surfaces that are in common use in high voltage equipment. Scanning electron microscopy (SEM) and energy dispersive X-ray analysis (EDX) have been reported to provide information on surface degradation as well as information on the chemical elements within the aged surfaces (Liu *et al.,* 2005; Sundrarajan *et al.,* 2004). The surface topography of the new and aged PE and PVC samples was examined using analytical scanning electron microscope (ASEM) JEOL-Model 6360A coupled with energy dispersive X-ray (EDX) module. Surfaces of these samples were platinum coated using JEOL Model JFC-1600 platinum coater before subjecting them to SEM surface analysis. A coating of ~80 nm was applied on these samples. An energy beam was set at 20 keV keeping the samples at a distance of 9 mm. The penetration depth was ~3 µm while the sample size was around 5 mm × 5 mm × 1 mm. None of the samples tested were cleaned prior to these measurements.

Results and Discussion

Results of this investigation show that PVC jacket material is affected when exposed to moisture, chemicals and petroleum products. PE material properties are also affected by petrochemical products, but to a much lesser extent as compared to PVC. This paper contains detailed results of several measurements carried out on new and aged samples. The results show that PE sheaths serve best when used on medium voltage underground cables that operate in GCC countries or countries with similar sub-soil terrain, as they will protect the cable insulation better than PVC.

Effect of moisture. It is well known that compared with PE PVC materials have much higher vapour transmission rate. As a result, underground cables buried in wet areas may suffer water treeing degradation at different rates if these two jacket materials are utilized while all other cable parameters are kept the same. Generally, water treeing leads to degradation of XLPE insulation. Consequently, cables having water treeing degradation exhibit reduced levels of the retained AC breakdown strength. Two of the important parameters to assess the extent of insulation deterioration caused by water treeing include the retained AC breakdown strength (E_r) of aged cable samples and water tree characteristics. Therefore, two types of aged cable samples were subjected to the following investigations: (i) breakdown studies as per high voltage time test (HVTT) method and (ii) water treeing and microscopic investigations. Table 2 gives the average breakdown strength (E_b) for five samples of each of the two types of non-aged cable samples and also compares the average retained breakdown strength (E_r) for aged samples of these cables. The values in parenthesis show the range of scatter in these values which is similar to the values reported by Al-Arainy *et al.* (2007) for non-aged XLPE cables of 50 mm^2 conductor cross-section. The ratios of E_r of aged cable samples and the E_b of the new cable samples with PE and PVC jackets are compared. The results clearly show that electrical breakdown strength decreases with aging in the AWTT protocol for both cable types. This decrease is larger for cables with PVC jackets than with PE jackets.

In addition, samples of the two types of the cables aged for 510 days were used for detection and investigation of water trees. Forty insulation slices, each of 0.45 mm thickness, were prepared from each of the aged cable types. These were prepared from two samples of each cable type that had exhibited two of the lowest breakdown voltages as per HVTT method.

Table 2. HVTT average breakdown voltage of non-aged and aged samples in AWTT (Aging time = 510 days).

XLPE cable	Before aging		After aging		
with sheath type	Breakdown voltage (kV$_{rms}$)	E_b (kV$_{rms}$/mm)	Breakdown voltage (kV$_{rms}$)	E_r (kV$_{rms}$/mm)	E_r/E_b (%)
PVC	189.7 (148.6 ~ 217.7)	42.16 (33~45)	127.5 (118~131.9)	28.34	67.2
PE	174.4 (170~188.7)	38.75 (34~41.93)	135.9 (124.7~146)	30.19	77.9

In each case, 20 slices were cut from both the sides of the cable insulation near the point (within a few centimeters) where the breakdown had occurred during the HVTT. These were stained and then subjected to microscopic examination. Total number of bow-tie and vented water trees as well as the length and the number distributions of such trees were measured in these slices.

No vented tree was detected in any of the samples of all the four cable types. This indicates good insulation as well as semi-conducting screen material and cable extrusion process. However, many bow-tie trees were detected in various cable samples. All bow-tie water trees ≥ 10 μm in one insulation slice were systematically measured and data of water tree length distribution was compiled for both the cable types. Such measurements are summarized in Table 3. The results show that cables with PVC outer sheath suffer some what more and longer water trees as compared to similar cables used with PE outer sheath.

Table 3. Bow-tie water tree length distribution

Length range (μm)	Total no. of trees	
	PVC sheath	PE Sheath
≤ 25	5	5
26 – 50	15	13
51 – 75	10	9
76 – 100	7	5
100 – 200	6	5
≥ 200	1	0

The longest trees were also measured in 20 insulation slices for each cable type. From these measurements, the range of maximum tree length (L_m) was derived for each cable; the results are given in Table (4). This table confirms that the longest trees are generally observed in a PVC sheathed cable. In addition to the above, the bow-tie tree number density (n_t) i.e. number of bow-tie trees per mm^3 of the insulation volume was also determined as illustrated in Table 4. In this case too, the cable with PVC outer sheath has the maximum (n_t) value. Thus, PE outer sheath is better than PVC outer sheath toward the propensity of water treeing degradation of the cable insulation, as well.

Table 4. Maximum tree length range (L_m) and tree number density (n_t)

Cable type	L_m (μm)	n_t (no./mm^3)
PVC sheath	170 – 260	1.31
PE sheath	120 – 210	1.25

Effect of chemicals and petrochemicals. When PVC is heated in presence of air and temperature, it suffers a loss of mass. Fig. 2 shows the measured loss of mass value with aging period. It shows that when PVC is exposed to chemical and petrochemical products, the loss of mass increases, which is more significant for longer aging periods. The increase in loss of mass for NaCl and $CuSO_4$ is minimal (see dotted line), whereas it is significant when PVC is exposed to petrol and diesel. It is clear that prolonged exposure of petrochemical products can significantly increase the loss of mass value thereby affecting the cable jacket's integrity. On the contrary, PE does not suffer any such loss of mass.

The mechanical properties (e.g. tensile strength and elongation at break) are also affected by exposure of cables to the chemical and petrochemical products. When PVC sheathed cables were subjected to 61 days of exposure to NaCl, $CuSO_4$

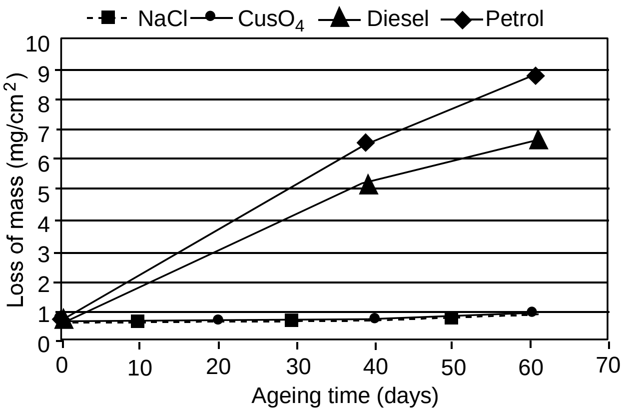


Fig. 2. Effect of exposure to petrochemicals on the loss of mass of PVC.

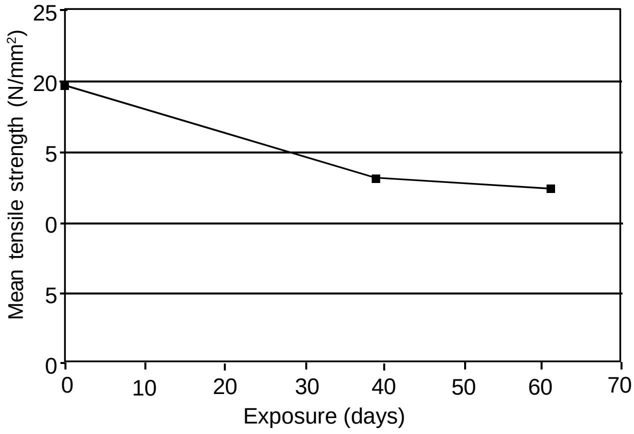


Fig. 3. Effect of exposure to petrol on the tensile strength.

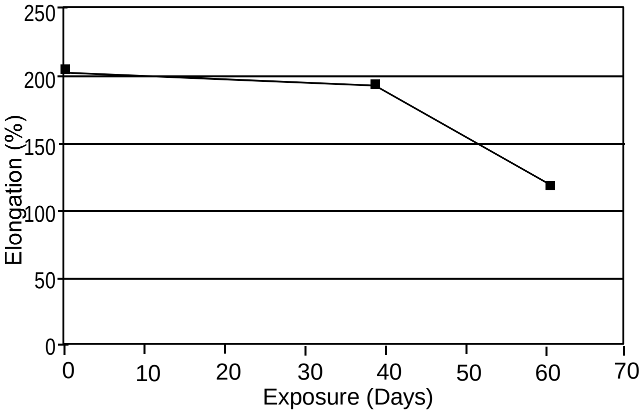


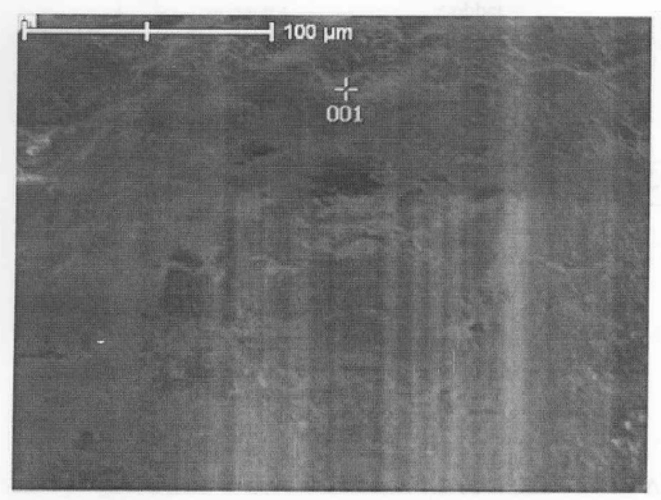
Fig. 4. Effect of exposure to diesel on the elongation at break of PVC.

or diesel, the tensile strength decreased by 10-20%. However, with exposure to petrol, as shown in Fig. 3, the decrease in tensile strength was 30-40%. This shows that petrol has the most adverse effect on the tensile strength of PVC jacket. When PE jacketed cables were exposed to the same level of chemical and petrochemical products, the decrease in tensile strength was in the range of 10-20% only. Thus, PE had less effect even under petrochemical exposure than PVC.

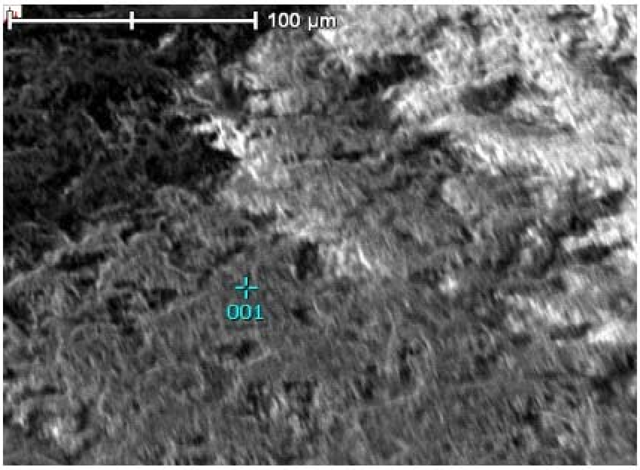
Similarly, the elongation at break values of cable jackets, as shown in Fig. 4, were also affected when exposed to chemical and petrochemical products. Here maximum reduction was observed for PVC when exposed to diesel, as diesel makes PVC more rigid, thereby reducing the elongation at break. Regarding PE, the influence of exposure to selected chemicals and petrochemicals was mostly <5%. Hence, PE jacketed cables are less influenced by petrochemical products investigated in this study when compared with PVC jacket cables. It should be noted that generally PVC material has ~33% lower tensile strength and ~70% lower elongation at break than the PE material which makes it more suitable for cable jacketing applications.

SEM images can provide a qualitative estimate of the type and extent of surface degradation. Such images were captured under a magnification of 500 for unaged as well as aged PVC and PE samples. The unaged samples generally exhibited smooth texture with only some debris. However, the aged samples had surface degradation and contamination deposits. PVC showed more surface degradation with rougher surface having micro-cracks, residues and contaminants, while PE surface showed same deposits of contamination.

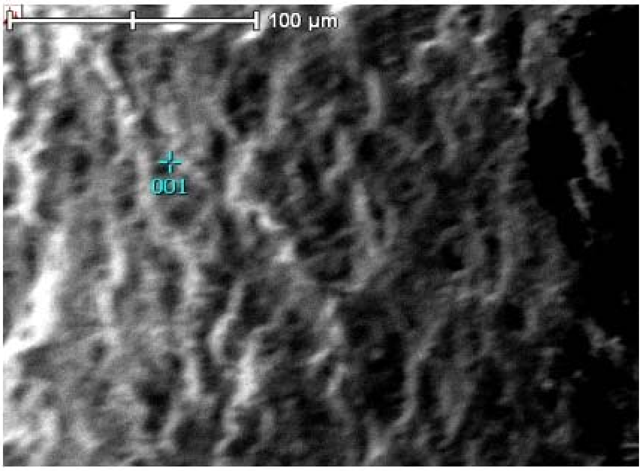
Each of the SEM images was associated with EDX results as well (Fig. 5). All the examined aged surfaces exhibited quantitatively various degrees of increase in oxygen and



(a)



(b)



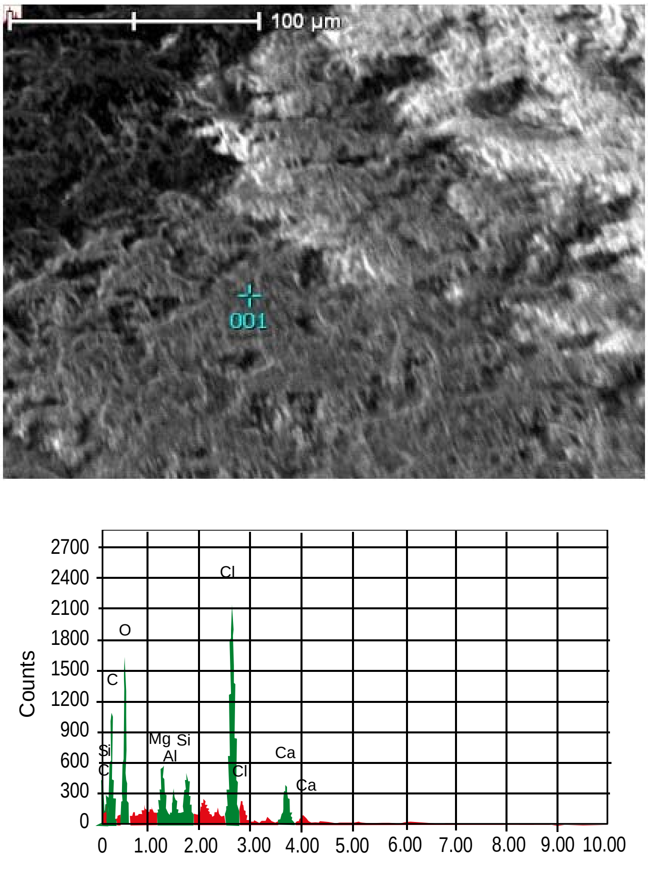
(c)

Fig. 5. SEM image of PVC sheath: (a) new sample, (b) aged under petrol for 61 days, (c) aged under aqueous ionic solution of NaCl for 61 days. (magnification = 500).

decrease in carbon levels. Samples with a higher percentage of O_2 have a lower percentage of carbon. In PVC samples, chlorine also had a high content. It is interesting to note that reaction of PVC with petrol has increased its Cl_2 content, whereas exposure to $CuSO_4$ reduced Cl_2 from the PVC molecules on the surface of samples.

The EDX data was used to determine the cationic percentage of carbon, oxygen and other major elements that were found on the surface of PVC and PE samples when these were exposed to chemical species and petroleum products for 61 days. Fig. 6 shows a selected case of SEM and EDX spectrogram of a PVC sample exposed to petrol. The ratio of cationic content of oxygen and carbon ($\eta = O_2/C$) can be used to determine the order of degradation which these petrochemicals impart to PVC and PE materials. These results are summarized in Table 5 which indicate the highest value $(\eta)_{PVC} = 2.48$ due to the effect of petrol on PVC, which is followed by other species in the following order:

Petrol > Diesel > $CuSO_4$ > NaCl



Element	(keV)	Mass %	Error %	At %	Cation (K)
C K	0.277	41.09	0.26	52.47	16.8640
O K	0.525	40.77	0.51	39.08	41.8579
Mg K	1.253	2.30	0.17	1.45	3.1713
Al K	1.486	0.98	0.17	0.56	1.5742
Si K	1.739	1.34	0.14	0.73	2.5757
Cl K	2.621	10.74	0.16	4.66	27.0914
Ca K	3.690	2.77	0.26	1.06	6.8655
Total		100.00		100.00	

Fig. 6. SEM surface profile and EDX spectrogram of a PVC sample exposed to petrol for 61 days.

Table 5. Cationic percentage in PVC samples obtained by the EDX surface analysis and comparison of η values for PVC and PE.

Cations	New	Aged under			
		NaCl	$CuSO_4$	Diesel	Petrol
C	62	47.5	44.5	37.7	16.86
O	28.6	42.6	54.0	49.35	41.9
Cl	6.1	3.6	0.7	9.76	27.1
Na	—	2.7	—	—	—
Si	3.2	1.4	—	—	2.6
Al	1.9	1.2	0.7	1.0	1.6
Cu	—	—	0.1	—	—
$(\eta)_{PVC}$	0.46	0.9	1.21	1.31	2.48
$(\eta)_{PE}$	0.61	0.4	0.28	0.51	0.96

It is gratifying to note that this order is consistent with the degradation noticed on the loss of mass and mechanical properties of PVC. In case of aged PE samples, the η_{PE} values are smaller than on PVC as shown in Table 5, thus further substantiating that PE is comparatively more prone to the deteriorating character of chemical and petroleum products investigated here and thus shall exhibit relatively much better performance when used as sheathing material on high voltage cables designed for underground applications.

Conclusion

Following conclusions are drawn from this experimental investigation:

1. PE sheathed cables show performance superior to that of similar cables sheathed with PVC, under wet accelerated aging conditions.
2. When PVC is exposed to chemicals such as NaCl and $CuSO_4$, the magnitude of its loss of mass value increases by ~40% with aging time. However, when it is exposed to petrol and diesel oils, the magnitude of loss of mass increases several folds and thus the effect of petroleum products on deterioration of PVC is much stronger than ionic chemicals.
3. When PE and PVC are exposed to chemicals and petro-

chemicals, their mechanical properties are affected. PVC sheath becomes soft when it is exposed to petrol and its tensile strength decreases by 40% with ~60 days period of exposure. PE sheath becomes harder when exposed to diesel; as a result its elongation at break decreases by 40% for ~60 day exposure period. Generally, petrol and diesel have more severe effect on PVC sheaths as compared to the influence of chemical species investigated.

4. SEM surface analysis exhibits different levels of surface degradation of PE and PVC due to their long exposure to petrochemical species. EDX analysis shows that the most severe degradation of PVC is due to petrol and diesel. However, PE was found to suffer much less effect than that on PVC when these are exposed to NaCl and $CuSO_4$.
5. A comparison of PE and PVC material shows that PE has better properties such as tensile strength, elongation at break, much lower water transmission as well as much lower degradation when exposed to moisture and petrochemicals. Therefore, PE sheaths may serve the best when used on high voltage underground cables that operate in Saudi Arabia and will protect the cable insulation better than PVC.

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