Failure investigation of an underground low voltage XLPE insulated cable

Anwar Ul-Hamid, Khaled Y. Soufi, Luai M. Al-Hadhrami and Ahsan M. Shemsi
Center for Engineering Research, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

Abstract

Purpose – This paper aims to determine the effect of exposure of underground electrical cables to chemically contaminated water.

Design/methodology/approach – Visual inspection and photography were carried out to record the appearance of electrical cables. Failed and un-failed cable samples were collected and analyzed using light microscopy, scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy and Fourier transform infrared spectroscopy. Sand and water samples were chemically tested for contaminants.

Findings – Underground low-voltage 0.6/1-kV cross-linked polyethene insulated cables belonging to a chemical production plant suffered failure after four years of service. Excavation of the cable trench revealed that the cables were buried in sand polluted with chemically contaminated water. The cables were discolored and covered with corrosion deposits. Experimental results indicated that the cable insulation was heavily degraded and the outer jacket of polyvinyl chloride exhibited cracks that had penetrated through its thickness. Water and sand surrounding the cable were found to have high concentrations of ammonia. Mechanical testing of the cables indicated high values of stiffness that could contribute to the formation of cracks at the surface.

Practical implications – It was concluded that contamination in the water had degraded the cable, resulting in the development of a network of branched cracks within the cable insulation through which water could permeate, leading to eventual failure of the cable. Accelerated degradation took place due to exposure to the contaminated environment, which promoted aging and brittleness. Continued exposure of electric cables to contamination would lead to power failures and plant shutdowns.

Originality/value – This paper provides an account of a failure investigation of low-voltage electrical cable buried underground. It discusses the role of contaminated environment in the eventual failure of electrical cable due to corrosion. This information will be useful for plant engineers and project managers working in any industry that makes use of chemicals.

Keywords Corrosion, Microscopy, Failure investigation, Chemical process

Paper type Case study

1. Introduction

Most utilities and industrial plants make extensive use of low- and medium-voltage cables. Cable design generally consists of an insulation material, metallic shield and jacketing. Although insulation failure is usually the final breakdown mode in cables, it is rarely the primary cause. Defect-free polyethylene cables operated within temperature limits and under dry conditions can last 40 years or more. Unfortunately, cable insulation is often subjected to severe conditions including contaminated water, overheating, damage during installation and high-voltage stresses. These lead to premature failures in service. Through appropriate tests conducted on failed cable samples, the most probable cause of failure can be understood.

This paper reports an investigation into the failure of low-voltage (0.6/1-kV) cross-linked polyethene (XLPE) insulated cables that formed part of an underground distribution circuit serving a production facility. The cables suffered failure after four years of service. The failure investigated in this study was a line-to-ground issue that affected the space heater cable for a pump. The cable trench at the site was excavated to expose the buried cables. Two cables of 4×4 mm^2 dimension had failed. Sand surrounding the failed cables appeared to be polluted with contaminated water. The sand was blackish in color and gave off an unpleasant odor indicating fouling with chemicals. It was reported that this location had been flooded in the past with methyl diethanolamine $CH_3N\,(C_2H_4OH)_2$ (MDEA) from a nearby tank. Samples were retrieved from the failed cables. Un-failed cable samples also were obtained from another nearby location where cables had been buried in sand that was exposed to uncontaminated water. The source of underground water was an elevated water table in the region. Sand and contaminated water samples were removed from the location of the failed cables. The objective of this study was to assess the extent of cable damage, determine the most probable cause of failure and provide recommendations.

2. Experimental procedure

2.1 Cable materials

The cables were constructed of four-stranded copper conductors with diameters of 2.5, 4, 6, 10 or 16 mm^2 and

The current issue and full text archive of this journal is available on Emerald Insight at: **www.emeraldinsight.com/0003-5599.htm**

Anti-Corrosion Methods and Materials
62/5 (2015) 281–287

[ISSN 0003-5599]
[DOI 10.1108/ACMM-02-2014-1352]

Received 10 February 2014
Revised 5 May 2015
Accepted 31 May 2015

covered with XLPE insulation (red, yellow, blue and green in color) of 0.7 mm thickness (Figure 1). The cables had galvanized double steel tapes (DST) of 0.2 mm in thickness for armoring and a flame-retardant polyvinyl chloride (PVC) outer black sheath with a dimension of 1.8 mm^2.

2.2 Analysis of cable and sand samples

Scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS) were used to examine surface features of the cable samples and determine their elemental composition. The samples were coated with Au to reduce charging effects in the SEM (Model: JEOL JSM 5800LV). The secondary electron mode was used for imaging at an accelerating voltage of 20 kV, and microchemical analysis was undertaken using an Oxford EDS detector fitted with an ultra-thin window. Sand samples were analyzed using SEM-EDS technique. The surface of the PVC jacket was studied using Fourier transform infrared (FTIR) attenuated total reflectance (ATR) with an infrared spectrometer (Model: Nicolet 6700 FT-IR).

2.3 Water analysis

Contaminated water samples were retrieved from the failure site and analyzed in the laboratory using standard analytical methods (SM, 2005).

2.4 Mechanical testing

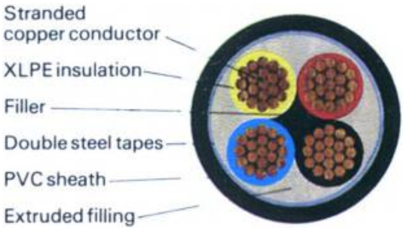
Mechanical testing was conducted to determine the tensile strength and Young's modulus of the cable in accordance with ASTM D638 standard with test speed of 20 mm/min.

3. Test results

3.1 Visual inspection

The cables were buried in a trench and were exposed to sand contaminated with MDEA, due to leakage from a nearby tank. The collected cable samples were inspected visually and photographed. A typical example of a failed cable obtained from the site is shown in Figure 2. It was observed that the DST was corroded and was brownish in color. It was fragile and easily breakable. The color of the filler was also brownish and had corrosion traces from the DST. XLPE insulation was darkened and the Cu conductors showed signs of corrosion in the form of spots. The average thickness of the outer PVC jacket of the cables was found to be 2.2 mm. Visual inspection did not reveal any sign of holes, cracks or other defects at the jacket surface. Some discoloration was observed, probably due to exposure to contaminated water and/or aging. Some cable samples without electrical connections had been buried in the sand in an uncontaminated location for a period of 12 months. These unused samples were retrieved and inspected. All cable components were found to be in a good condition unaffected by their environment.

Figure 1 Cable construction (4-core cable 0.6/1-kV, Cu, XLPE, DST, PVC)



3.2 Light microscopy

Surfaces and cross-sections of failed and unused cables were examined using light microscopy at low magnifications. The surface of outer PVC jacket of a failed cable is shown in Figure 3. White deposits originating from contaminated water covered the entire surface, while small holes (encircled) were evident in the crevices (Figure 4). A cross-section revealed air/gas bubbles or inclusions in the outer and inner surfaces of the jacket wall. The presence of brown-colored deposit is also clear in Figure 5, indicating penetration of contaminant constituents possibly in solution with water into the jacket material through defects. Eventual evaporation of water had left behind contaminant precipitate.

Penetration of contaminated water was further facilitated by the presence of relatively coarse defects such as cracks at the surface, as seen in Figure 6. The presence of brown-colored deposit within the crack is an indication that the crack had been present during service and did not occur during cable retrieval. It may have occurred during cable installation. Cracks can form due to mechanical damage during cable installation. Several cracks that propagated across the jacket wall were observed, as illustrated in a typical example shown in Figure 7. It is clear that water with dissolved contaminants could easily penetrate through these cracks into the inner sections of the cable.

The cracks could originate from defects present within the PVC jacket during manufacturing, installation or service. Figure 8 was obtained from an unused cable similar to the one under investigation in this study and served to highlight the existence of manufacturing defects. Air inclusions were found close to the outer and inner surfaces of the PVC jacket. These

Figure 2 Typical example of a failed XLPE cable obtained from the site

Figure 3 Surface morphology showing a hole at the surface of a failed PVC cable (40×)

Figure 4 Cross-section of the outer PVC jacket showing air inclusions at the inner and outer surfaces (18×)

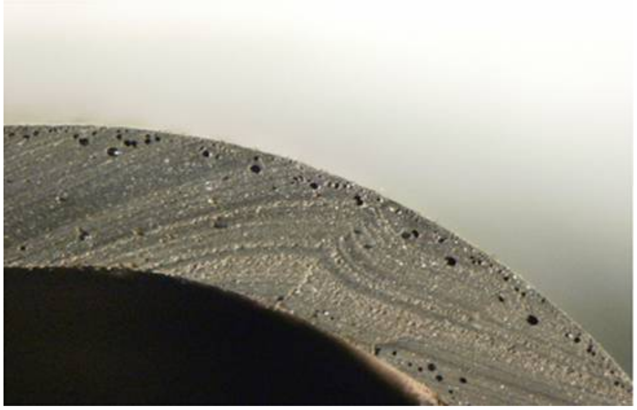
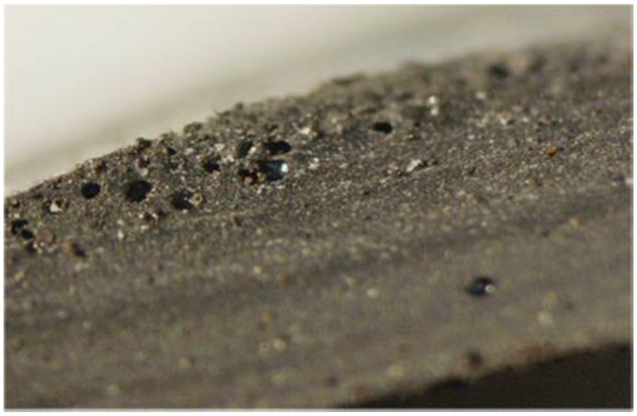


Figure 5 Cross-section of the outer PVC jacket showing air inclusions and brown-colored contamination (40×)



inclusions were formed during the extrusion process when the insulated cable was covered with the PVC jacket.

3.3 Analysis of contaminated water

The results of chemical analysis of underground water collected from the failure site as well as from a location in proximity to it but unaffected by the chemical spill are shown in Table I. The pH levels of water collected from the failure site indicate that the solution was mildly basic in nature. The ammonia level was very high, which was consistent with the blackish color and bad odor of the sand present in the failed cable trench. Results obtained from the nearby location that was not influenced by the chemical leak were typical of water solution from the elevated water table at that location.

Figure 6 Relatively coarse crack at the surface of PVC jacket (18×)

Figure 7 Cross-section image showing a transverse crack in the PVC jacket (40×)

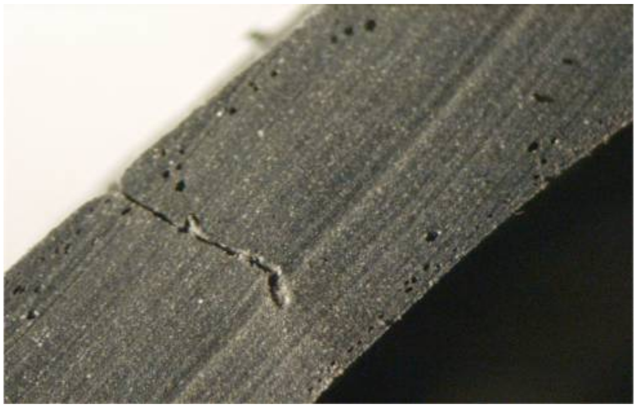


Figure 8 Cross-section of unused cable showing air inclusions at the inner and outer surfaces of the PVC jacket (18×)

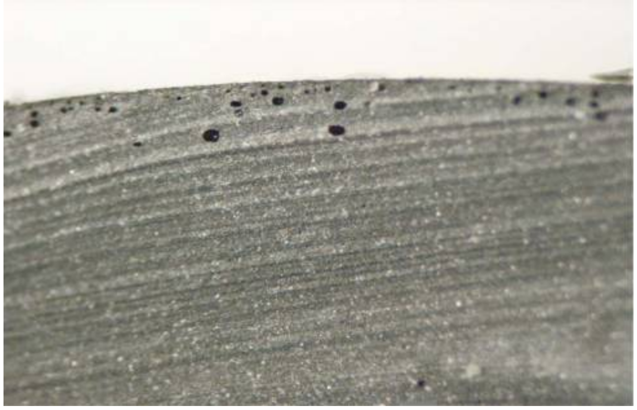


Table I Results of chemical analysis of water samples

No.	Parameter	Failure site	Nearby site
1	pH	7.78	7.99
2	EC [m mhos/cm][a]	9.5	33.5
3	TDS, 180°C[b]	6,065	28,920
4	Ammonia (mg/L)	4,887	0.905
5	Bicarbonate (mg/L)	1,133	340
6	Fluoride (mg/L)	61.87	4.12
7	Chloride (mg/L)	413	10,167
8	Sulfate (mg/L)	3,505	4,685
9	Nitrate (mg/L)	14.56	34.99
10	Calcium (mg/L)	214	1,017
11	Iron (mg/L)	0.24	0.15
12	Potassium (mg/L)	73.1	331
13	Magnesium (mg/L)	37.8	464
14	Sodium (mg/L)	195	5,429
15	Silica (mg/L)	14.23	10.73
16	Zinc (mg/L)	0.28	0.08

Notes: [a] EC: electric conductivity and [b] TDS: total dissolved solids at 180°C (soluble parts)

3.4 Analysis of sand

Sand samples were collected from the failure site and from a nearby location within the same facility and were analyzed using SEM/EDS. The analysis results are shown in Table II. Apart from Si and O originating from SiO_2, the analysis shows the presence of elements such as C, S, Mg, K, Ca, etc.

3.5 Scanning electron microscopy

Cable components such as the outer and inner surfaces of the PVC jacket, filler, DST, XLPE and conductors were examined using SEM-EDS. The aim was to observe the surface morphology to record any cable material degradation and to detect the presence of any foreign material at the inner sections of the cables using microchemical analysis. The results of such analysis conducted at various sections of a failed cable are summarized in Table III. Elemental analysis at the inner surface of the PVC jacket revealed the presence of significant amounts of S at this location. The contamination present at the inner surface of PVC in the failed cable is shown in the SEM micrograph of Figure 9. The metal armoring was made of galvanized steel, and large amounts of S were detected within the deposits formed at the surface of steel, as shown in the X-ray mapping images of Figure 10. Sulfur was detected within the filler material and also within the inner surface of the XLPE material, as shown in Figure 11. In the SEM images, sulfur existed as small bright deposits on top of a layer of Cu present on the XLPE inner surface. During visual inspection, this deposit appeared as a black layer within the inner XLPE surface. The outer surface of the XLPE was blackened and showed the presence of Cu. Moreover, the presence of Fe and O at the metal surface suggests the formation of an Fe-oxide compound. The blackened region of the Cu wire in the failed cable also was analyzed and was found to contain significant amounts of S and O. Sulfur could originate from sand, as the latter showed the presence of S in chemical analysis (Table II). Elevated seawater table is the most likely source of sulfur in sand, as seawater contains appreciable amounts of sulfates. Seawater in the study area floods the cable trenches frequently. Foreign material observed within the cable is thought to originate from the surrounding sand environment.

Table II SEM-EDS analysis of sand samples in weight%

Elements	Failure site	Nearby site
C	3.7	6.3
O	50.7	55
Mg	16.0	8.3
Al	0.24	0.46
Si	18.2	25.6
S	3.84	0.18
Cl	–	0.27
K	0.6	0.81
Ca	5.6	1.57
Fe	1.05	1.36

3.6 FTIR analysis

The surface of the PVC material was studied using an FTIR ATR spectrometer. Deconvolution of peaks and the appearance of bands at around 1,720 cm^{-1} provided information on the level of oxidation produced. Table IV shows some infrared (IR) group vibrations associated with PVC and used for finger-printing.

In Figure 12, the characteristic FTIR spectrum of pure PVC is given for reference and analysis. This spectrum shows all group frequencies matched with the given frequencies in Table IV. The encircled region in Figure 12 shows no clear peak but does exhibit a little kink. Figure 13 shows the FTIR spectrum of an unused cable. This cable showed all the characteristic peaks of PVC. Closer inspection revealed that there were small changes occurring in the band at 1,720 cm^{-1}. This band can be attributed to the carbonyl stretching (CO-stretching 1,720 cm^{-1}). This is an indication that dehydrochlorination occurred during manufacturing or storage of the cable.

Dehydrochlorination, followed by oxidation in the presence of oxygen, resulted in the formation of carbonyl ketone. The peak at 1,720 cm^{-1} is a typical carbonyl peak and its presence is an indication of the buildup of this breakdown product. Another reason for the presence of this peak in the newly formed PVC jacket is due to a stabilizer (dioctyl phthalate: DOP) used as an additive in the synthesis (CO-stretching 1,740 cm^{-1}). As the carbonyl peak appears at 1,720 cm^{-1} then, most probably, the PVC jacket underwent an aging process, and this is evident from Figure 13. The band at 844 cm^{-1} is designated for C-Cl stretching vibration. In unused cable, it appears at higher the energy side of 872 cm^{-1}, which means C-Cl stretching has occurred in an environment where the C-Cl bond is much stronger than that in the pure PVC. A broad band also can be observed in the 3,500-3,200 cm^{-1} region, which is indicative of a hydrated material.

The spectra of failed cables (see the typical example shown in Figure 14) exhibited group frequencies similar to those stated for PVC. They also showed a band at 1,720 cm^{-1}, an indication of the aging process, and a broad band between 3,500-3200 cm^{-1}, showing the presence of hydrated water. Some cables showed two sharp bands in this region, indicating

Table III Summary of SEM/EDS analysis of failed cable

	Chemical composition, wt%								
Elements	Outer PVC (contaminated)	Inner PVC (contaminated)	Outer metal	Inner metal	Outer filler	Inner filler	Outer XLPE	Inner XLPE	Cu wires
C	–	–	–	–	–	34.9	84.3	–	
O	53.6	10.1	28.5	22.5	43.9	35.5	7.7	3.6	66.23
S	2.23	23.9	1.22-11	5.3-19	1.3	1.4	0.2	4.2	17.42
Cl	11.3	12.7	0.7	8.8	7.1	32.3	0.4	0.3	
Ca	12.1	0.9	–	–	1.4	12.8	–	–	
Zn	–	44.9	–	62.4	34.6	–	–	–	
Fe	0.9	7.5	69.6	1.0-66	11.6	–	–	–	2.39
Mg	17.2	–	–	–	–	–	–	–	
P	–	–	–	–	–	–	–	–	
Na	–	–	–	–	–	–	–	–	
Si	2.6	–	–	–	–	–	0.5	–	0.54
K	–	–	–	–	–	–	–	–	
Cu	–	–	–	–	–	–	6.8	92	13.42

Figure 9 Secondary electron SEM image of the deposit seen at the inner surface of PVC sheath in the failed cable

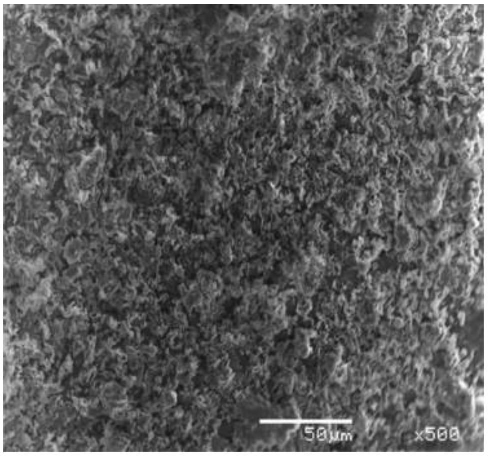
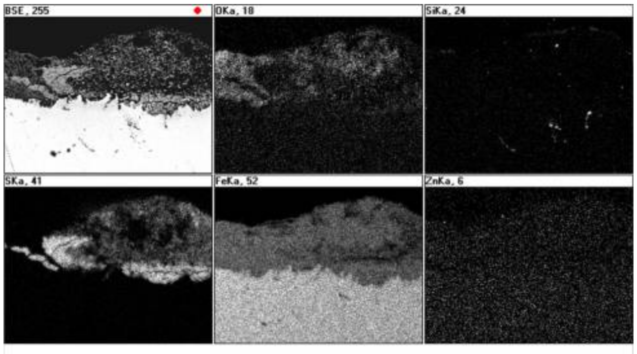


Figure 10 X-ray map images obtained from a cross-section of metal armoring of the failed cable showing the presence of S within the deposit present at the surface of metal



an N-H stretching vibration of the nitrogen-containing compound present as monoamine in the PVC, which could be attributed to the effect of ammonia contamination on the cable jacket (Brenntag Canada Inc, 2014).

Figure 11 Secondary electron SEM image of the deposit observed at the inner surface of XLPE insulator material in failed cable

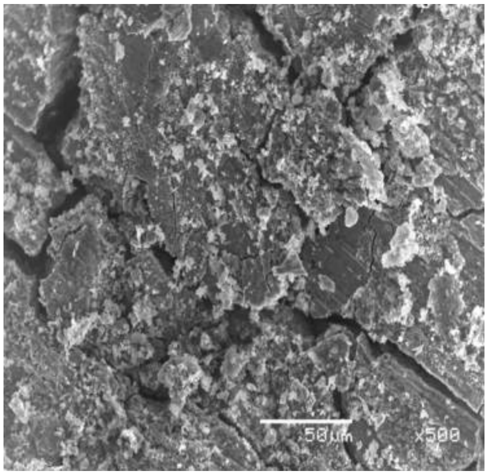


Table IV Different FTIR vibrational group frequencies associated with PVC

C-H stretching	2,890-2,958 cm^{-1}
CH_2 deformation	1,339 cm^{-1}
CH rocking	1,240-1,257 cm^{-1}
Trans-CH wagging	961 cm^{-1}
C-Cl stretching	844 cm^{-1}
Cis-CH wagging	2,890-2,958 cm^{-1}
CO stretching (non-PVC vibration)	1,720 cm^{-1}

Generally, PVC is one of the most widely used plastics that can be processed to form both flexible and rigid finished articles. The production of PVC articles in most processes is through injection molding or extrusion. One of the major problems is the heat generation during extrusion of the PVC jacket over the insulated cables, which sometime causes thermal degradation. Degradation of the PVC proceeds by a dehydrochlorination process that results in the formation of long conjugated double bonds or polyene sequences

Figure 12 FTIR spectrum of a pure polyvinylchloride (PVC)

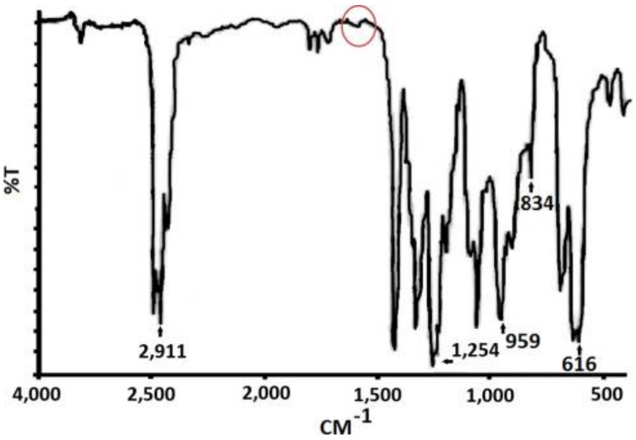


Figure 13 FTIR spectrum of the outer PVC jacket of new cable No. 9

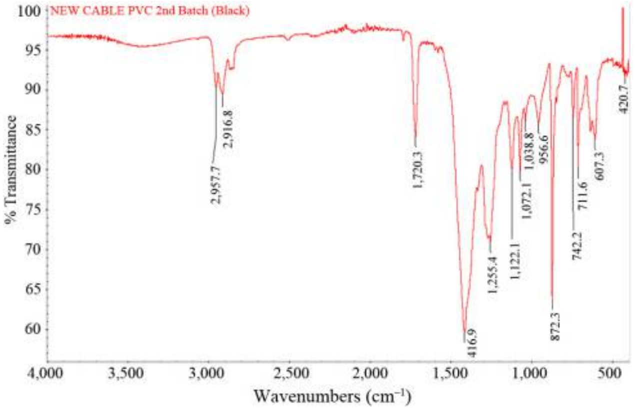
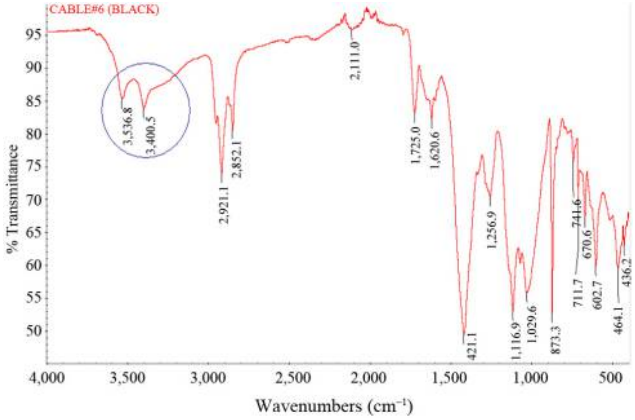


Figure 14 FTIR spectrum of the outer PVC jacket of failed cable



(OCH-CHO)n, thereby causing a color change. The dehydrochlorination process becomes even more rapid in the presence of oxygen, which then causes the formation of carbonyl groups (Torikai and Hasegawa, 1999). The polyene sequences formed during degradation can lead to cross-linking and chain scissions. The properties of PVC are well-documented in the literature (Summers *et al.*, 1992; Carroll, 1994; Wenguang and Mantia, 1996).

The main disadvantage of PVC is that it weathers easily with exposure to heat and/or UV radiation present in the sunlight. This effect is more pronounced in the presence of chemicals that are not compatible with PVC. Weathering effects manifest as surface discoloration and a loss of flexibility, eventually leading to increased brittleness and cracking. All cable jackets have defined permeability, which depends on the composition of the jacket and materials that are used as additives or fillers to the jacket (IEEE Std 1242-1999, 2005), but it normally takes large number of years to cause corrosion of the steel sheath.

3.7 Mechanical testing of PVC jackets

Visual inspection of cables revealed signs of aging, especially of the PVC jacket sections. In view of this, PVC jacket samples of failed and unused cables were subjected to mechanical testing to determine their tensile strength and Young's modulus. The test results are summarized in Table V.

The failed cable showed a higher value of Young's modulus, which indicates increased stiffness compared to the unused cable. The increase in stiffness can easily lead to cracks in the material, and as the failed samples were buried in the ground, it is safe to assume that the degradation in their mechanical properties was not primarily instigated by ultraviolet rays. The most likely reason for this brittleness is the polluted environment around the buried cables.

4. Mode of failure

The cables were exposed to an environment that had been heavily polluted with MDEA. Water analysis at the failed location showed large concentrations of ammonia. The presence of surface defects and cracks in the cable jacket allowed contaminated/polluted water to permeate the cable insulation and corrode the metallic sheath, which consequently allowed the contamination to reach the XLPE and copper conductors. The presence of contaminated water can cause the formation of a network of fine-branched cracks inside the XPLE insulation and may result in electrical short-circuiting to ground. This will degrade the electrical insulation capability of the XPLE insulation and lead to early insulation failure. The water and sand contamination present in the vicinity of the cables assisted the mechanism of failure by speeding up the corrosion process of the steel sheath and copper conductors. Short-circuiting will lead to localized overheating of the insulation. There was no evidence of electrical overloading of the cable.

5. Probable cause of failure

The most probable cause of failure was the presence of contamination in the vicinity of cables buried in the sand.

Table V Mechanical test results for the cable samples

Sample name	Maximum stress (MPa)	Strain at break (mm/mm)	Modulus (MPa)
Failed cable	10.99	0.99	29.676
Unused cable	11.06	1.28	23.656

Surface defects such as cracks observed at the surface of the PVC jacket aided in the failure process.

6. Recommendations

As a result of the findings of the failure investigation presented above, the following recommendations were formulated:

- Polluted ground contamination at the failure site should be removed and buried cables checked using DC voltage testing.
- A thorough examination of standard operation procedures and cable selection processes should be undertaken for the plants to ensure compatibility with appropriate national, international and company standards.
- Extensive evaluation should be conducted using the latest technologies available for the protection of cabling systems used in the industry, such as using waterproofing sheets with hydrophobic sand to prevent groundwater intrusion and corrosion.
- Proper arrangements should be made to avoid chemical spills in the future.

References

Brenntag Canada Inc (2014), "Material safety data sheet index", *HCI 1689/09A*, p. 5, available at: www.brenntag.ca

Carroll, W.F. Jr (1994), "Recycling postconsumer PVC bottles: technology and market development", *Journal of Vinyl Technology*, Vol. 16, pp. 169-176.

IEEE Std 1242-1999 (2005), "IEEE guide for specifying and selecting power, control, and special-purpose cable for petroleum and chemical plants", *[SM 2005] Standard Methods for The Examination of Water and Wastewater*, in Eaton, A.D., Clesceri, L.S., Roice, E.W. and Greenberg, A.E. (Eds), *21st, APHA, AWWA & WEF*.

Summers, J.W., Mikofalvy, B.K., Boo, H.K., Krogstie, J.M., Sell, W.A. and Rodriguez, J.C. (1992), "Examples of recycled vinyl products", *Journal of Vinyl Technology*, Vol. 14, pp. 165-170.

Torikai, A. and Hasegawa, H. (1999), "Accelerated photodegradation of poly(vinyl chloride)", *Polymer Degradation and Stability*, Vol. 63, pp. 441-445.

Wenguang, M. and Mantia, F.P.L. (1996), "Processing and mechanical properties of recycled PVC and of homopolymer blends with virgin PVC", *Journal of Applied Polymer Science*, Vol. 59, pp. 759-767.

Corresponding author

Luai M. Al-Hadhrami can be contacted at: luaimalh@kfupm.edu.sa

---