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CORROSION OF LEAD CONSTRUCTIONS BURIED IN SWEDISH SOILS

Göran Camitz and Tor-Gunnar Vinka

Swedish Corrosion Institute, Kräftriket, Building 23A, SE-104 05 STOCKHOLM, Sweden

Abstract
The corrosion properties of the lead metal buried in soils have been investigated in three separate studies: 1) a statistical evaluation of a large number of corrosion cases, which had occurred on the bare lead sheath of buried telecommunication cables, b) a long-term field exposure where the corrosion of lead panels, which have been buried and exposed in soil for several years, has been determined, and c) a study of the release and dispersion of lead in the soil around the test plates.

It was found that the corrosion, which leads to cable damage, appears as localised corrosion attacks, which are penetrating through the cable sheath. When such a damage occurs, and the cause solely is the corrosive properties of the soil (and not electric currents in the ground or galvanic connection to copper earthing electrodes), the corrosion rate is in the range of 100 to 250 µm/year, although a few cases with higher rates were observed.

The corrosion rates of the test panels in the long-term field study were generally low, both for the uniform (general) corrosion and the localised corrosion. The uniform corrosion is in the range of 0,1 to 2 µm/year and the localised corrosion in the range of 20 to 100 µm/year, although also here a few higher rates were encountered.

The study of the release and dispersion of lead, released in the corrosion process, in the soil near the test plates showed that almost all of the released lead was found in the corrosion products adhering to the metal surface or bound to soil particles within a few centimetres away from the metal surface.

One important conclusion is that lead has a good corrosion resistance in soil environments. It is believed that the high corrosion resistance is a result of the formation of a stable and protective layer of corrosion products on the metal surface, consisting mainly of lead carbonate and/or lead sulphate. It is suggested that the results of the investigations are applicable on buried lead pipes and other lead constructions in soil.

INTRODUCTION AND BACKGROUND

The corrosion of lead and other constructional metals are being investigated in a systematic and unique long-term field study. The reason why including the metal lead in the exposure program is that unprotected lead is widely used as cable sheath for buried telecommunication cables.

Lead sheathed cables buried in soil in Sweden

Lead was never used as a pipe material for drinking water in Sweden, and thus there are no lead pipes for tap water installed neither in the ground nor in buildings. However, there exist a huge amount of buried telecommunication cables with a bare lead sheath. Since Sweden is a large country with large distances between the communities the total length of lead sheathed telecom cables is very large. These cables were laid in the ground by the Swedish Telecommunication Administration during the period from the 1930's to the mid 1960's. After the mid 1960's newly laid cables had an outer insulation of polyethylene (PE). Beside these cables the

Swedish State Railways laid the same type of telecommunication cables, i.e. with an external lead sheath, along the railways during approximately the same period.

There are three types of tele communication cables laid by the Telecom Administrations: a) long distance cables, b) medium distance cables between communities and towns, and c) short distance cables within communities and towns. According to statistics at the Telecom Administration, the total length of bare lead sheathed cables is 160 000 km. Because of the introduction of opto- telecommunication technique most of the long and medium distance cables have been taken out of operation during the last 10-15 years period, but these "dead" cables have been left in the ground. It is estimated that there are approximately only 30 000 km bare lead sheathed cables in operation today.

Concerning telecommunication cables buried along the railways there is no reliable statistics concerning the total length of bare lead sheathed cables. However, taking into account the total length of railways the total cable length should be well above 50 000 km. Cables installed in modern times are, however, not buried directly in soil but laid in underground canalisation.

With respect to the large amount and economical value of these buried lead sheathed cables, reliable knowledge about the corrosion behaviour of lead in various types of soil is of great importance. This is the background why the two administrations mentioned have supported the Swedish Corrosion Institute's long-term field exposure program in soil, both financially and with delivery of test material.

EXPERIMENTAL

The investigation consists of three separate studies: 1) a statistical evaluation of a large number of corrosion cases, which had occurred on the bare lead sheath of buried telecommunication cables, b) a long-term field exposure where the corrosion of lead panels, which have been buried and exposed in soil for several years, has been determined, and c) a study of the release and dispersion of lead in the soil around the test plates.

Cable corrosion statistics

In the statistical investigation a number of damage reports from the Swedish Telecom were analysed. Such reports are drawn up when a cable damage has occurred, and they include i.a. the cause of the damage. During earlier decades the damage investigation and the reports were quite detailed when the cause of the damage was corrosion. The cable-to-soil potential was recorded and soil samples were taken and analysed with respect to chemical composition, pH-value and soil resistivity.

In this investigation 300 such corrosion cases where the bare lead cable sheath had been penetrated by corrosion were studied. 71 of these cases had been caused by the corrosive influence of the surrounding soil. The remaining 229 cases had been caused either by galvanic corrosion caused by metallic connection to copper earthing electrodes or by stray current corrosion caused by stray currents in the ground from D.C. traction. The latter two types of cases were excluded from the study, since it was solely concentrated on the influence of the soil on the corrosion process. Since the original thickness of the lead sheath and the age of the cable at the time when the lead sheath was penetrated by the corrosion, were known, it was possible to calculate the average rate of the localised corrosion in each case. The reports came from 8 telecom districts, roughly equally distributed over the country. This part of the study has been described in more detail in an internal report at the Swedish Corrosion Institute (1).

Field exposures of test plates

Test sites

Nine test sites in soil have been established in different parts of Sweden. See figure 1. All test sites were established in flat terrain, which means that there are no strong ground water movements. The soil at the test sites is given in table 1.

The soil at the sites is naturally stratified, relatively uniform and has never been dug over. There is no risk of stray-current corrosion. The ground water table in the test trenches is roughly 1 m below ground level in the early autumn and has moderate seasonal variations. Specimens could thus be placed both above and below the groundwater table for study of its effects on corrosion. An exception are the test sites nr.8 and 9 where there is only one test level and where the ground water table is far below the test level.

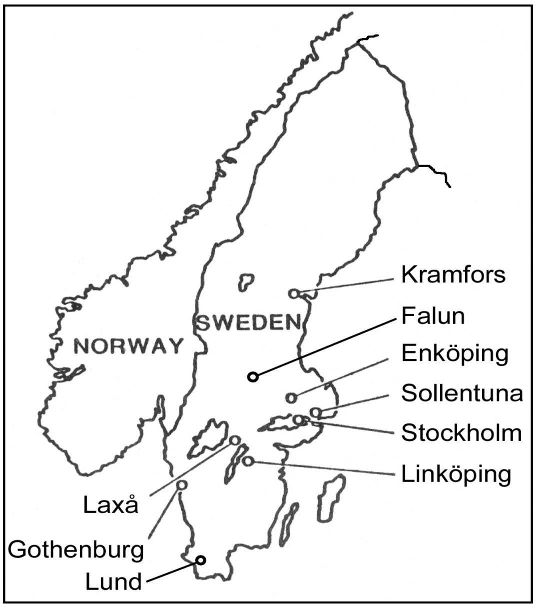

Figure 1. Location of the test sites in soil.

The soil types at the test sites

The clay at test site nr.1 (Enköping) is a pure glacial clay with low content of organic matter, sulphur compounds and chloride. The site is situated on cultivated land. The clay at test site nr.2 (Sollentuna) is post-glacial clay. This site is situated on cultivated land and very close to the shoreline of a lake, which probably explains the quite high content of organic matter and sulphur compounds. The clay at test site nr.3 (Kramfors) is a post-glacial black silty clay with an extremely high sulphide content and an anaerobe soil environment. The test site is situated on cultivated land near the large river Ångermanälven, which is originating in the manganese and iron sulphide rich mountains in the northern part of Sweden. This may explain the high sulphide content in the clay. When this clay is aerated its colour changes rapidly from black to light grey and the sulphides are oxidised to sulphate resulting in a lowering of the pH- value one or two pH-units.

The clay at test site nr.4 (Gothenburg) is a marine clay. The site is situated on cultivated land near the seawater, which explains the very high chloride content. Since the organic content is high this clay has the prefix gyttja (mud). The clay at test site nr.5 (Stockholm) is a post- glacial gyttja (muddy) clay. The site is situated on cultivated land and not far from the shoreline of Lake Mälaren, which probably explains the high content of organic matter and sulphur compounds. The soil at test site nr.6 (Laxå) is a pure peat soil consisting of almost only organic matter. The organic matter and the sulphur compounds is the result of the historic putrefaction of plants and animals during the formation of this soil. The site is situated in forest land.

The soil at test site nr.7 (Linköping) is a homogenous and well aerated sand with quite high resistivity. The soils at test sites nr.8 (Falun) and nr.9 (Lund) are similar to each other with the exception of the soil resistivity. Both soils are till soils, which is a coarse, inorganic non-sorted type of soil that is encountered in moraine terrain. Both soils are well aerated. The test sites 7, 8 and 9 are situated in forest land.

All these soils are representative of Swedish and northern European geology. They are also encountered quite often further down south in Europe.

Table 1. Characterisation of the soil at the Swedish Corrosion Institute's test sites.

Test site	Depth of test level	Type of soil	Resis-tivity	Water content	Organic content	pH value	Carbon-ate	Chloride	Sulphur compounds mg S/kg dry soil		
	m		ohm-cm	wt% of wet soil	wt% of dry soil		wt% $CaCO_3$ of dry soil	mg Cl^-/kg dry soil	Sul-phide S^{2-} - S	Sulphate SO_4^{2-} - S	Total sulphur
1. Enköping	0.7	Heavy clay	3 290	31	1,6	6,6	0,18	20	7	21	190
	1.7	Very heavy clay	3 450	32	0,7	6,9	0,16	20	7	29	150
2. Sollentuna	0.7	Heavy clay	3 770	41	2,9	4,3	0,32	34	8	202	2 090
	1.7	Heavy clay	1 170	48	2,2	6,3	0,32	22	288	526	10 300
3. Kramfors	1,2	Silty clay	2 570	33	0,9	6,2	0,19	50	238	49	2 030
	2,2	Silty clay	1 430	30	1,9	6,8	0,19	60	347	47	1 240
4. Gothenburg	0.7	Heavy muddy clay	1 710	41	3,7	4,4	0,16	170	8	412	1 480
	1.7	Heavy muddy clay	345	54	4,6	7,4	0,22	2 200	82	322	14 600
5. Stockholm	0.7	Heavy muddy clay	5 220	43	2,8	4,2	0,18	30	8	188	1 840
	1.7	Muddy clay	1 050	51	4,5	5,4	0,15	140	19	758	6 400
6. Laxå	0.7	Fibrous peat	7 160	85	75	4,3	< 0,10	180	61	36	120
	1.7	Pseudo-fibrous peat	13 100	92	61	4,2	< 0,10	220	31	41	550
7. Linköping	0.7	Sand	262 000	7	0,5	5,7	0,12	20	< 5	6	90
	1.7	Greavelly sand	17 900	13	0,2	8,0	3,0	20	< 5	8	140
8. Falun	0,4	Sandy till	331 000	17	0,8	5,5	0,34	22	–	29	285
9. Lund	0,4	Sandy till	21 500	15	1,9	4,4	0,27	22	–	50	238

Soil analysis

The characters of the soils can be seen in **table 1**. The analyses were carried out on samples taken from the disturbed soil in the test trenches at a depth corresponding to the location of the metal specimens. Because of very high water content and the lack of heavy mineral particles in the organic peat soil at test site 6, the content of chloride and sulphur compounds is illusory high in this soil. The soil resistivities and pH values of the sandfills that surround some of the specimens at test sites nr. 1 - 7, measured about three years after start of exposure, are shown in **table 2**.

TABLE 2. Resistivity and pH value in the sandfills used at the test sites 1-6 measured about 3 years' after start of exposure.

Test site	Depth m	Resistivity ohm-cm	pH-value
1. Enköping	0,7 1,7	10 300 13 500	6,5 7,1
2. Sollentuna	0,7 1,7	18 500 10 900	6,8 8,1
3. Kramfors	0,7 1,7	14 900 12 000	5,9 6,7
4. Gothenburg	0,7 1,7	3 660 1 670	7,2 8,2
5. Stockholm	0,7 1,7	30 700 2 260	5,1 5,6
6. Laxå	0,7 1,7	56 900 45 500	6,4 7,0

Tested material and specimen design

The lead tested has the following chemical composition in mass percent: Cu: 0.13, Sn: 0.07, Ag: 0.023, Bi: 0.008, Fe: 0.006, Ti: <0.02 and Pb: remainder. The composition corresponds to the type of lead, which is used as cable sheath on buried telecom cables. The dimensions of the test panels is 150 × 150 × 3 mm. Triplicate specimens were used throughout.

Position of the specimens in the soil

The test panels have been buried in trenches at the test sites - one trench for each planned withdrawal of panels. At test site nr.1 – 7 there are in total five test trenches at each test site. In each trench there is an upper test level at a depth of about 0,7 mm and a lower one at about 1,7 m. See **figure 2**. When the trenches were refilled, an attempt was made to return as far as possible the excavated soil according to its original stratification. The groundwater table fluctuates with the season of the year between these two levels. During the period from late autumn with frequent rainfall to early spring after the snow melting the groundwater table is high at test sites with clay soil. The upper test level may then be covered with groundwater and thus the soil at the upper level periodically is water saturated.

The test panels are exposed standing in a vertical position in a row in the original soil above and below the groundwater table. Furthermore, a set of panels above and a set below the groundwater table have been entirely embedded in a sand-fill at site 1-6.

At test site nr.8 and 9 there are only three test trenches and only one test level in each trench. In these trenches the copper panels were pushed into position in the trench wall at a depth of 0,4 m below ground surface. At these two test sites the ground water level is, as already mentioned, far below the test levels.

In total, approx. 450 lead test panels have been buried in the field exposure program.

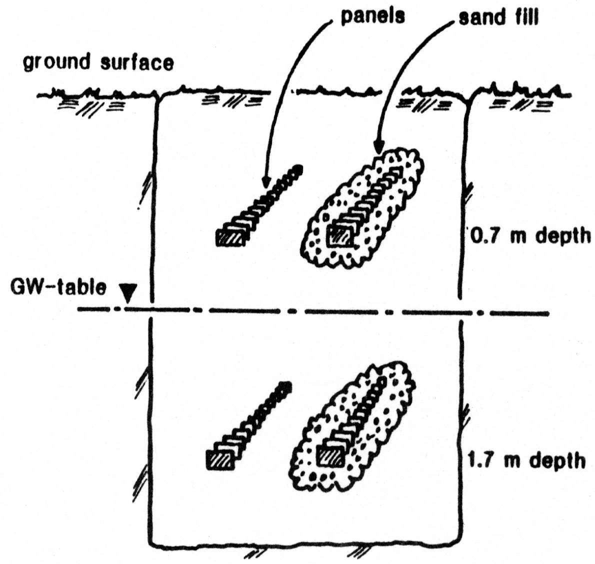

Figure 2. Position of the test panels in the trenches at the soil test sites no.1-7.

Evaluation of corrosion rate

The corrosion rate of all the specimens has been determined as mass loss and is expressed as average penetration. After removal of loose soil, the specimens were pickled in saturated ammonium acetate (CH_3COONH_4) solution using repeated pickling at room temperature. The depth of localized corrosion areas was measured throughout with a focusing microscope.

One weakness in the evaluation of corrosion rates is the fact that lead is a quite soft metal and that is easily may be mechanically damaged. In the evaluation it was found that some panels were damaged either by the soil or by tools during the excavation procedure. In some cases it was difficult to separate corrosion attacks from mechanical damages. This might in a few cases have rendered in false measurements of the deepest attack. It might also have influenced the weight loss determination in such a way that the uniform corrosion falsely has been given a higher value than the true value.

Measurement of lead dispersion into the surrounding soil

Recently the concern about the release and dispersion of i.a. lead in the soil surrounding lead sheathed cables was brought up in the environmental discussion in Sweden and other countries. A fear for a lead contamination of the groundwater, and thus of the drinking water, has been expressed.

The test panels that were still being exposed at the field test sites provided a unique opportunity to study this matter. In addition to the corrosion rate, the distribution of the dissolved lead between corrosion products and the surrounding soil could be studied, as well as the lead concentration profile in the surrounding soil.

RESULTS AND DISCUSSION

Cable corrosion statistics

The result of the calculation of the rate of localised corrosion attacks is presented in **table 3**. It can be seen that the majority of corrosion rates are in the range of approximately 100 – 250 µm/year, although some extreme values between 400 and 700 µm/year were observed in the cable corrosion reports. The mean value of these corrosion rates is 181 µm/year. A typical lead sheath thickness of a short distance telecom cable is 1,2 – 1,6 mm. Using the medium value of corrosion rates the cable sheath would be perforated after approx. 7 –9 years in average in a soil with corrosive properties.

Table 3. Rates of localised corrosion attacks on buried lead sheathed telecom cabled.

Parameter	Value
Number of damage cases	71
Lowest localised corrosion rate	38 µm/year
Lower quartile	93 µm/year
Medium value	156 µm/year
Upper quartile	240 µm/year
Highest localised corrosion rate	700 µm/year
Mean value	181 µm/year
Standard deviation	125 µm/year

Field exposures of test plates

The corrosion rate (uniform and localized corrosion) of the test panels after the latest withdrawal of specimens, which were buried in original soil, is shown in **figure 3**. The corrosion rate (uniform and localized corrosion) of the test panels after the latest withdrawal of specimens, which were buried in sand fill at test sites 1-6, is shown in **figure 4**. The exposure period is seven years for panels from test sites 1, 2, 4, 5, 6 and 7 and five years for panels from test sites 3, 8 and 9. The corrosion rate is presented as uniform corrosion, and as localised corrosion. The corrosion rates are given as mean value for triplicate test panels (three test panels having been exposed near each other at the same position in the trench). The corrosion rates are based on evaluation of approx. 40 single test panels. The corrosion rate (uniform and localised corrosion) for each single test panel at each of the three withdrawals has been reported earlier in an internal report at the Swedish Corrosion Institute (2).

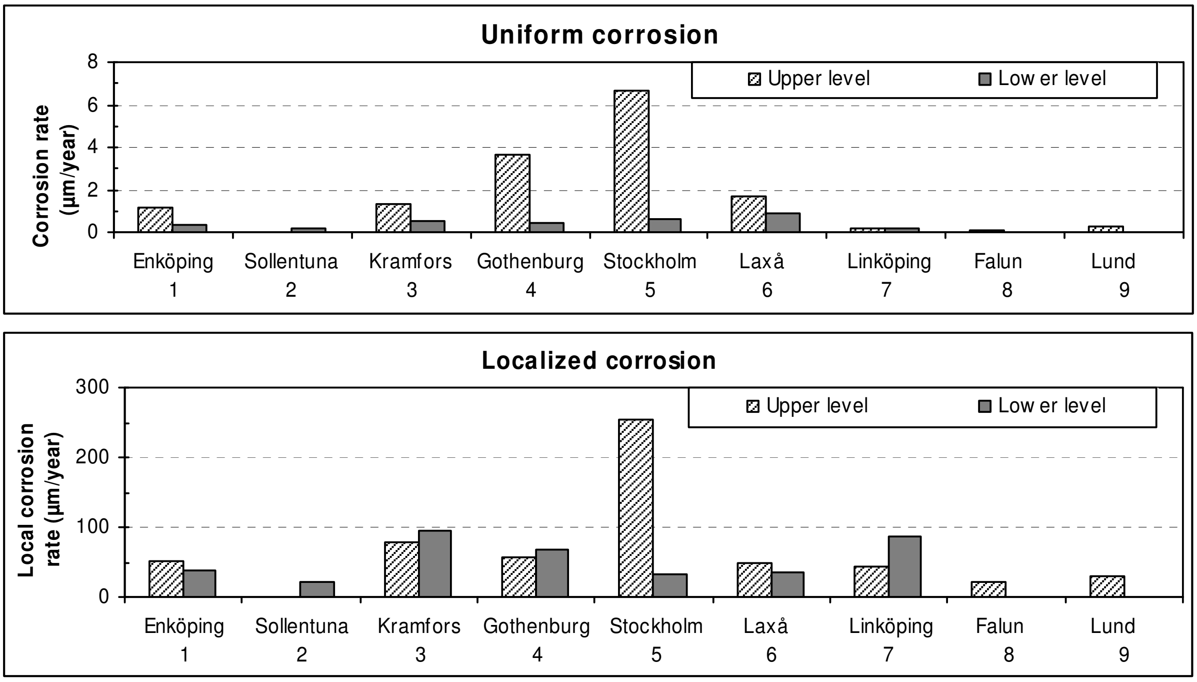

Figure 3. Corrosion rate (uniform and localised corrosion) of the lead test panels after the latest withdrawal of specimens, which had been buried directly in original soil. At test sites 1-7 test panels had been buried at an upper and at an lover test level. At test sites 8-9 test panels had been buried only at one test level.

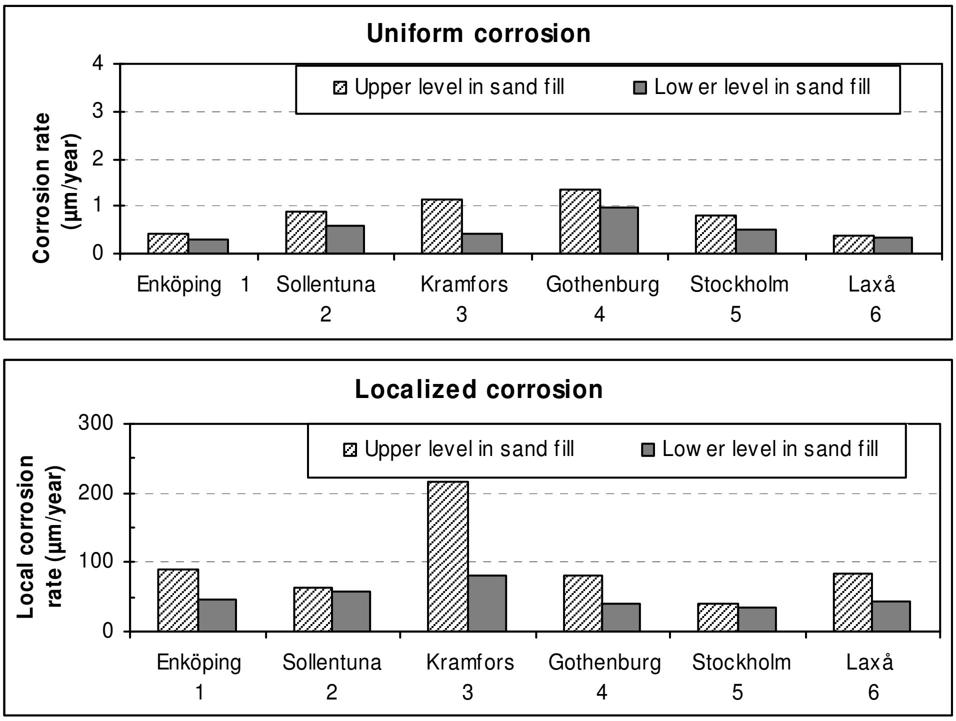

Figure 4. Corrosion rate (uniform and localised corrosion) of the lead test panels after the latest withdrawal of specimens, which had been buried in sand fill at test sites 1-6. The test panels had been buried at an upper and at a lover test level.

From figure 3 and 4 it appears that the uniform corrosion is low and that it is in the range of approximately 0,1 – 2 µm/year. However, a couple of extreme values of 4 and 6,5 µm/year were observed, but these can be questioned because of uncertainties in the evaluation procedure, i.e. deep mechanical damages of these test panel might have been falsely reflected as corrosion loss in the weight loss measurements. The localised corrosion is in the range of 20-100 µm/year, although also here a few extreme values of approx. 200 and 250 µm/year were determined. These extremes can be questioned of the same reason as for the extreme values for the uniform corrosion, i.e. the difficulty to separate corrosion attacks from mechanical damage on these test panels caused either by the soil or the excavation procedure.

The reason for the low uniform corrosion is probably the fact that lead ions, which are released in the corrosion process, form a stable and protective layer of corrosion products on the metal surface, consisting of various modifications of lead carbonate ($PbCO_3$) and/or of lead sulphate ($PbSO_4$), (3).

One striking observation is that both the uniform and the localised corrosion in most cases is higher at the upper test level than at the lower. The reason to this is probably, as already hinted at, that the oxygen transport to the metal surface is more rapid in the non-water saturated soil above the groundwater table, supporting the cathodic corrosion reactions in the corrosion cells.

Lead dispersion into the surrounding soil

Since this investigation is going on only a few results are available, i.e. from field test site no. 6 and no. 7. At test site no. 6, with a peat soil, the average corrosion rate (uniform corrosion) was 1,4 µm/year. The lead content in the soil was only elevated in a region of 0-2 cm from the test panels. At a distance of 5-10 cm from the test panels the lead content in the soil was 13 mg Pb/kg dry soil. In a reference sample of soil 12 m away from the test site the lead content was 9 mg/kg dry soil.

At test site no. 7, with a sandy soil, the average corrosion rate was 0,2 µm/year. The analyses of lead content in the soil showed the same pattern as at test site no. 3. At a distance of 5-10 cm away from the panels the lead content was 24 mg/kg dry soil and in two reference samples of soil, 7 and 11 m away from the test site, the lead content was 17 mg/kg dry soil.

The results so far show that almost all of the corroded lead may be found very close to the exposed test panels and that the content of lead in the soil at a distance of only 10 cm from the exposed test panels is of the same magnitude as in a reference soil sample. However, more investigations, particularly from other soil types, are needed before the results can be taken as generally valid.

CONCLUSIONS

Based on the evaluation of corrosion damage reports for telecom cables and on the results in the field exposure investigation with buried lead test panels, some important conclusions can be drawn:

- Lead has a good corrosion resistance in soil environments

- The reason for the high corrosion resistance is the fact that lead ions, which are released in the corrosion process, form a stable and protective layer of corrosion products on the metal surface, consisting of various modifications of lead carbonate ($PbCO_3$) and/or of lead sulphate ($PbSO_4$)

- Corrosion damage to the lead cable sheath on buried telecom cables, caused by the corrosive properties of the soil, is very rare with respect to the very large total length of the cable network. When such a damage occurs the corrosion rate seems to be in the range of approximately 100 – 250 µm/year, although some extreme values between 400 and 700 µm/year were observed in the cable corrosion reports.

- The dominating cause of corrosion damage of buried lead sheathed cables are stray currents in the ground emerging from D.C. railways (stray current corrosion) and metallic connection to copper earthing electrodes (galvanic corrosion).

- Evaluation of the corrosion rates of buried lead test panels showed low corrosion rates, both for the uniform (general) corrosion and the localised corrosion. The uniform corrosion is in the range of approximately 0,1 – 2 µm/year. However, a couple of extreme values of 4 and 6,5 µm/year were observed, but these can be questioned because of uncertainties in the evaluation procedure. The localised corrosion is in the range of 20-100 µm/year, although also here a few extreme values of approx. 200 and 250 µm/year were determined. These extremes can be questioned of the same reason as for the extreme values for the uniform corrosion.

- The analyses of the soil, which was surrounding the test panels, showed that almost all of the released lead was found either in the corrosion products on the metal surface or bound to soil particles very close to the metal surface.

- The observations in the study concerning the dispersion of lead from the solid lead metal into the surrounding soil may be used in the environmental protection debate, in which lead contamination of ground waters from buried lead constructions is discussed

- The results in this study can be applied on other lead constructions in the soil, e.g. lead pipes

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