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Comparison of the Effect of Copper Cable Corrosion in Soil, Water and Atmospheric Environments on Telecommunication Data Transmission Speed

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ABSTRACT:
Copper cables are widely used in telecommunication equipment as data transmitters. One of the problems related to the use of these cables is the corrosion of the cable surface caused by the environmental conditions of the place of use. Corrosion of cable surface leads to change of surface condition and formation of corrosion products on it. In this article, samples of copper cable with a diameter of 0.4 mm have been tested as a telecommunication platform for information transmission. Some parts of this cable that have already been used in the environmental conditions of soil, atmosphere and water environment were prepared. The chemical composition of the corrosion product on the cable surface was identified using X-ray diffraction analysis. On the other hand, the electrical resistance of the investigated cable and a piece of healthy and uncorroded cable were measured using an ohmmeter. Also, to determine the data transfer speed, the desired cable was placed in the path of a modem and the noise and data transfer speed measurement software of ADSL service provider companies was used. The results showed that the corrosion products formed on the surface of the cable are different in different environments. The electrical resistance of the corroded cable in the aqueous environment was the highest value and the lowest value was obtained in the ambient atmosphere. The data transmission speed was the highest in the healthy cable without corrosion and the lowest in the corroded underground cable. It was also proved that the corrosion products on the surface of the corroded cable in the soil are of CuO type and have greatly increased the electrical resistance of the cable and led to an increase in noise and a significant decrease in transmission speed.

KEYWORDS: Copper Cable, Corrosion, Data Transmission, Electrical Resistance.

1. INTRODUCTION

The process of copper corrosion in soil is a complex category that depends on many variables. This complexity is so much that on the one hand, archaeological excavations estimate the life of copper pieces buried in the soil to be hundreds of years [1] and on the other hand, cases of severe corrosion of copper in the soil in water pipes or equipment and telecommunication cables have been reported. [2]. This means that under certain conditions, soil can be considered as a serious corrosive agent for copper, and under appropriate conditions, copper is able to show good resistance against corrosion reactions[1].

Soil generally consists of three main parts: particles, humidity and gas [3]. In general, soil properties such as humidity rate, amount of oxygen, revival potential, pH, electrical conductivity, and microbial activities can affect soil electrical resistance and consequently corrosion reactions [4].

Soils with high acid intensity and pH value less than 4, which often have a large amount of chloride or sulfate, create the most corrosive conditions for copper and its alloys [1]. In this situation, if the soil contains a significant amount of coal, this corrosiveness will increase again. Due to the large amount of carbon, coal forms a galvanic connection with the copper cable. In this connection, copper is more anodic than carbon and undergoes severe corrosion. Carbon also acts as a regenerator of dissolved oxygen in the soil. Oxygen regeneration in soil is a common cathodic reaction that can occur in soil. Therefore, in soils containing coal, the corrosion rate of copper is also high [5].

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The most important effective factor in the corrosion of copper in the atmosphere is the presence of water. Corrosion of copper only in contact with air and at ambient temperature is generally not important from an engineering point of view. Therefore, water must condense on metal surfaces or be precipitated by rain. Then this water evaporates and leaves compounds on the surface. Hence, an important factor in atmospheric corrosion is the duration of "wetness" [6].

When water evaporates, whatever is dissolved in it is deposited on the copper surface. Therefore, if these residual compounds are aggressive and corrosive, the corrosion rate of copper increases after water evaporation. Compounds and components that are usually placed on the surface of copper due to condensation or due to the presence of rainwater include oxygen, carbon dioxide, ammonia, and sulfur and nitrogen oxides [2]. In addition to these gases, two other factors that affect the atmospheric corrosion of copper are temperature and suspended particles in the atmosphere [1].

The researchers studied a wide range of different metals and alloys exposed to the ambient atmosphere and found that the corrosion rate of copper is generally not high in any environment. However, the highest copper corrosion rate exists in marine environments [7].

In addition to the ambient atmosphere, copper and its alloys may also be used in aqueous environments. Although the performance of copper in these conditions is often reliable and safe, sometimes failures, disruptions and breakdowns are also observed in copper lines. For example, in aqueous environments, in the presence of ammonia, copper may undergo SCC type stress corrosion [1].

In most researches, the results related to surface water indicate the occurrence of pitting corrosion and SCC in copper alloys. But some parts show different corrosion behavior due to exposure to lower temperatures or deeper areas. The speed of water flow as well as the temperature and amount of oxygen dissolved in it have a significant effect on copper corrosion [1].

In aerated water, the chemical composition of water and pH determine the corrosiveness of water. In fact, in these conditions, any form of corrosion can occur depending on pH, chemical composition, water flow rate and stress [1].

Copper cables may be widely used in atmospheric or aquatic environments for telecommunication data transmission. In data transmission, the transmission medium acts as a physical path between the sender and the receiver. Copper cables provide a guided path for the propagation of waves. Data cannot be sent as it is generated in the transmission media and it depends on the type of transmission medium. Usually, data is transmitted in the form of electromagnetic signals in copper wires. In general, in the media or medium of guided transmission, the type of medium plays an important role in the transmission of waves [8].

In the issues related to data transmission through guided media, such as copper cables, in addition to the bandwidth of the transmission media, transmission disturbances such as noise, attenuation, and delay also affect the speed of data transmission. In fact, these disorders act as transmission barriers in the communication system and cause the difference between the received signal and the transmitted signal. The main cause of attenuation is attributed to the resistance and capacitance properties of the transmission lines. Any factor that causes a change in the signal propagation speed during the transmission medium, causes a change in the phase location between different frequencies and creates a delay disturbance [8].

Despite the widespread use of copper cables in telecommunication networks in short distances; No complete research has been reported on the effect of environmental conditions on signal-to-noise ratio and telecommunication data transmission speed. In this article, the effect of copper cable corrosion in soil, atmosphere and water environments, on the occurrence of interference in the transmission of electromagnetic signals and finally the change in telecommunication data transmission speed is investigated.

2. RESEARCH MATERIALS AND METHODS

In this article, almost pure copper cable with 99% purity and diameter of 0.4 mm was examined. The process of doing the work was that first, samples of the copper cable which had corroded under the soil were prepared. These cables were used underground as part of a telecommunication communication system in the Safashahr region, Fars. In addition, samples of corroded cable exposed to water and air atmosphere were also prepared as studied samples. Healthy and corrosion-free samples of this cable were also prepared with similar specifications.

In order to evaluate the corrosion conditions and identify the type of corrosion products formed on the cable, X-ray diffraction analysis, which is one of the modern methods of material identification, was used. The X-ray diffraction pattern of the corroded cable in the soil was prepared by a Philips model XRD machine. The diffraction pattern was drawn by a Cu-kα lamp with a wavelength of 1.54060 angstroms at 2θ angles between 10 and 90 degrees.

An ohmmeter with an accuracy of 0.1 ohm was used to determine the rate of changes in the electrical resistance of the copper cable in different environments and due to the formation of different surface deposits. In this way, the electrical resistance of the samples was determined.

Also, in order to determine the speed of data transfer in different samples, one of the common noise and speed measurement software of companies providing ADSL services was used (Speeedchecker.ir). In this method, the desired cable is placed in the path of a modem and the speed of data transmission along with noise and other characteristics was determined.

3. RESULTS AND DISCUSSION

The result of X-ray diffraction analysis for the samples of corroded copper cable under soil, water and air is shown in Figs. 1, 2 and 3, respectively.

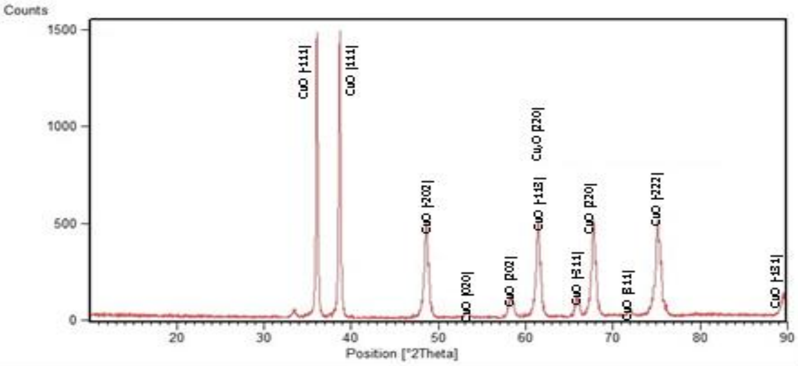

Fig. 1. Diffraction pattern of X-ray diffraction (XRD) results to determine the composition of copper cable corrosion product in soil.

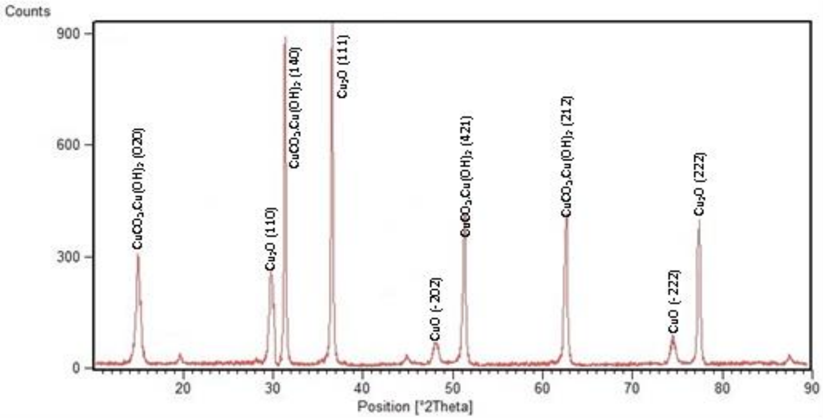

Fig. 2. Diffraction pattern of X-ray diffraction (XRD) results to determine the composition of copper cable corrosion product in water.

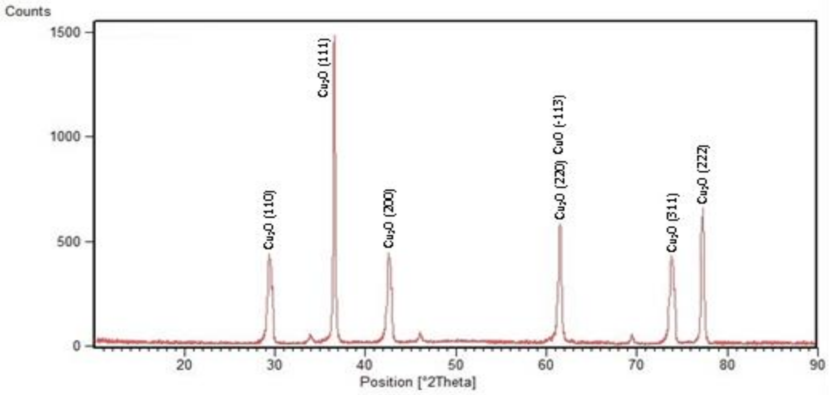

Fig. 3. Diffraction pattern of X-ray diffraction (XRD) results to determine the composition of copper cable corrosion product in air atmosphere.

As can be seen from Fig. 1, the corrosion product in soil is copper oxide II (CuO). Of course, there are also partial diffractions from copper oxide I (Cu2O), which are insignificant and can be ignored.

In Figs. 2 and 3, it is clear that the product of copper corrosion in air is cuprite (Cu2O); While in the aqueous environment, in addition to Cu2O, significant diffractions from malachite with the chemical formula of CuCO3.Cu(OH)2 are also observed.

Tables 1 and 2 show the types and characteristics of corrosion products formed on the surface of copper cables in different corrosion environments.

Table 1. Types of corrosion products formed on the surface of copper cables in water and air.

No	Corrosive environment	Type of corrosion products
1	Soil	CuO
2	Water	$CuCO_3.Cu(OH)_2$ و Cu_2O
3	Air	Cu_2O

Table 2. Characteristics of corrosion products formed on the surface of corroded cables.

No	Corrosion product name	Chemical formula	Crystal structure	Color	Cell volume Å^3	Density g/cm^3
1	Cuprite	Cu_2O	cubic	Red	76.87	6.14
2	Malachite	$CuCO_3.Cu(OH)_2$	monoclinic	Dark green	364.35	4.00
3	Tenorite	CuO	monoclinic			

In Table 3, the value of electric resistance of healthy and corroded cables in different environments is included. The results show that the phenomenon of corrosion in the underground copper cable has led to a significant increase in the electrical resistance of the cable and its value has changed from 0.8 Ω for the healthy cable to 1.7 Ω for the corroded cable.

Table 3. The results of the electrical resistance test of different samples.

No	Sample type	Type of surface layer	Electrical resistance (Ω)
1	Corroded in soil	CuO	1.7
2	Corroded in water	و Cu_2O $CuCO_3.Cu(OH)_2$	1.8
3	Corroded in air	Cu_2O	1.4
4	Healthy	--	0,8

Table 4 also shows the measurement results of telecommunication data transmission speed for healthy and corroded sample cables. The speed of data transmission in corroded copper cables is significantly reduced and the noise of the system increases as the amount of disturbing unwanted signals.

Table 4. The results of the data transfer speed measurement test for the studied copper cables.

No	Sample type	Average signal-to-noise .ratio (SNR)	Data transfer speed (downstream/upstream)
1	Corroded in soil	18.0/16.2 dB	7360/544 kbps
2	Corroded in water	17.5/15.3 dB	10204/525 kbps
3	Corroded in air	19.8/20.9 dB	10260/522 kbps
4	Healthy	21.3/25.3 dB	10260/525 kbps

In order to investigate these changes, the characteristics of the surface oxide layer formed on the copper cable in the environment should be considered. The ability of various materials, including CuO, to conduct electricity depends on the nature of their chemical bonds. Materials such as copper, which have a significant number of metallic bonds in their structure, generally show high electrical conductivity, and their free electrons simply move when applied to a potential difference [9]. The crystal structure of copper oxide II (CuO) with the scientific name tenorite is monoclinic. Fig. 4 shows a schematic of the crystal structure of CuO. As it is known, each copper atom is surrounded by four pairs of oxygen atoms at the corners of a parallelogram. Therefore, each oxygen atom is surrounded by four copper atoms at the corners of a tilted tetrahedron. In this structure, the network distances are as follows [10]: $d_{Cu\text{-}O}=1.95°A$, $d_{O\text{-}O}=2.62°A$, $d_{Cu\text{-}Cu}=2.90°A$,

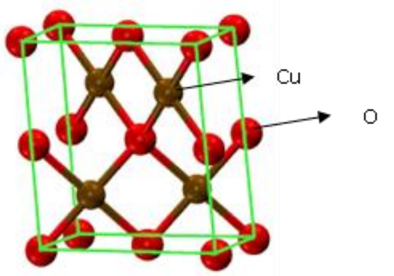

Fig. 4. Schematic of monoclinic crystal structure for copper II oxide (CuO)[10].

On the other hand, pure copper has an fcc crystal structure, a schematic of which is shown in Fig. 5. This structure is cubic with center faces occupied by copper atoms. In this structure, the lattice distances of copper atoms is $d_{Cu\text{-}Cu}=3.615°A$[10].

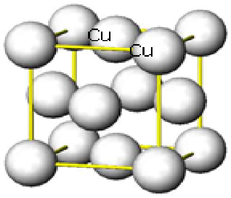

Fig. 5. Schematic of fcc crystal structure for copper [10].

What is known is that with the addition of oxygen to the crystal network of copper, in addition to changing the type of atomic arrangement that leads to the formation of a new crystal structure, the atomic distances are also reduced. Decreasing the atomic distances leads to a decrease in the mobility of charge carriers and, as a result, to a decrease in electrical conductivity. In other words, the special structure of copper oxide II (CuO) has caused a special electronic structure in a way that does not allow electrons to move in the network. The low concentration of charge carriers as well as the presence of low mobility carriers and the antiferromagnetic nature of CuO can be the reasons for the increase in electrical resistance of the corroded cable compared to the healthy cable. The mobility of electron holes and electric charge carriers in CuO is much lower than that of conductive copper cable. In an antiferromagnetic material, the valence electron moment tends to be in opposite directions. In this way, they neutralize each other and the net magnetic moment in this type of material is zero [11]. In other words, the magnetic resistance of CuO is very low. Therefore, the antiferromagnetic structure of CuO causes low mobility of electric charge carriers and increases resistance. As the results of tests measuring the electrical resistance of cables and data transmission speed show, increasing resistance leads to a decrease in data transmission speed. Another thing that can be said about the effect of cable surface oxidation on data transfer speed is that due to corrosion and the formation of a copper oxide layer on the cable surface, the effective cross-sectional area of the cable decreases. Since the amount of passing current and, in other words, the specific electrical conductivity of the cable is directly proportional to its cross-sectional area, it is expected that the surface oxide will reduce the ability to carry current. This decrease in conductivity and increase in electrical resistance, based on the results listed in Table 4, causes a decrease in the speed of data transmission through the corroded cable.

Regarding the corrosion of copper cables in aqueous and atmospheric environments, it can be pointed out that cuprite and malachite [12], the corrosion products of their surfaces, have different properties that lead to different performance of these cables in the telecommunication data transmission process. The difference in their crystal structure can be seen in Figs. 6 and 7. The difference in the crystal structure of these sediments has led to a fundamental difference in their electronic structure and conductivity. In the investigations related to the electronic behavior of various compounds, the important issue of forbidden energy band or band gap should be taken into consideration.

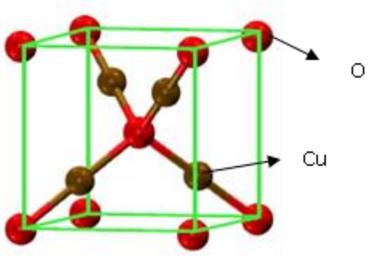

Fig. 6. Schematic of the cubic crystal structure for copper oxide I (Cu2O) [12].

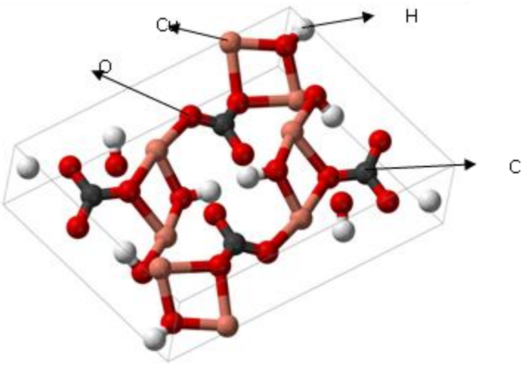

Fig. 7. Schematic of monoclinic crystal structure for CuCO3.Cu(OH)2[12].

In the electronic theory of materials, the band gap or forbidden energy band is defined as the energy range of a solid material in which no electronic state can exist. As Fig. 8 shows, in the electron band structure of solids, especially non-conducting and semi-conducting materials, the band gap is related to the energy difference between the top of the valence band and the bottom of the conduction band. The band gap is often expressed in electron volts (eV). In order for an electron to move from the valence band to the conduction band, the amount of energy equivalent to the band gap must be provided for it. Only the electrons transferred to the conduction band are able to move in the crystal lattice of the material and are used as electric charge carriers to conduct the electric current. If the valence band is completely full and the conduction band is completely empty, electrons cannot move in the solid. However, if some electrons are transferred from the valence band to the conduction band, an electric current can be established. Therefore, the band gap is an important effective factor in determining the electrical conductivity of a solid. In other words, materials with a large band gap act as insulators, and materials with a smaller band gap are used as semiconductors. In conductive materials such as copper, the valence and conduction bands overlap, and therefore, either they do not have a band gap at all or they have a very small band gap [11].

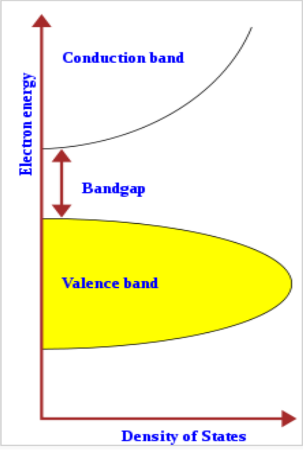

Fig. 8. A schematic of the band structure of a material to specify the forbidden band [11].

Each solid has its own band gap structure. This diversity in the band structure of materials is responsible for the wide range of electrical properties and characteristics observed in different materials. In semiconductors and insulators, electrons are limited and exclusive to some energy bands, so their movement and transfer to other areas is impossible [11].

In general, electrons are able to jump from one electron band to another electron band. In this regard, in order to jump the electron from the valence band to the conduction band, a certain minimum amount of energy is required for the transition. The energy required for this mutation is different in different materials.

The electrical conductivity of semiconductor materials is strongly dependent on the value of their band gap. The only electric charge carriers available for conduction are electrons that have enough energy to jump through the forbidden band and transfer to the conduction band. In fact, semiconductors are insulators with a relatively narrow band gap. The mobility of electrons plays an important role in the electronic behavior and determining the conductivity of the material.

Both cuprite and malachite compounds, which were formed on the surface of copper cable due to corrosion in different environments, are actually semiconductors that, if the energy of the forbidden band is provided, there is a possibility of electron jumping from the valence band to their conduction band. The energy required for the electron to jump to the conduction band is obtained through the application of electric fields, heat or light radiation [11]. The value of the band gap of these compounds is specified in Table 5.

Table 5. Energy values related to the band gap of copper corrosion products in different environments [11].

No	Compound name	Chemical formula	Band gap (eV)
1	Tenorite	CuO	1.2-1.9
2	Cuprite	Cu_2O	2.02-2.17
3	Malachite	$CuCO_3.Cu(OH)_2$	2.44

As Table 5 shows, the energy gap related to malachite is significantly larger. In fact, the band gap of malachite is larger and therefore it is more difficult to transfer electrons from the valence band to the conduction band. Therefore, it is expected that in case of forbidden energy band or band gap width, malachite shows a higher electrical resistance than cuprite, against the movement of electrons. Fig. 9 shows a schematic of the gap band related to these compounds for comparison.

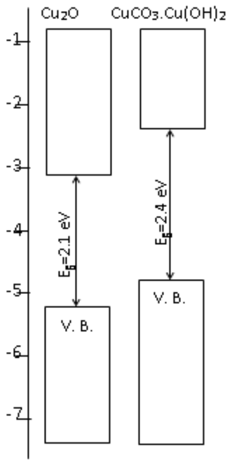

Fig. 9. Schematic of the forbidden band width in cuprite and malachite compounds.

The justification mentioned for the difference in electrical resistance of cuprite and malachite compounds based on the width of the forbidden energy band or band gap is consistent with the results of the electrical resistance measurement in Table 3. As the results of the electrical resistance test in Table 3 show, the lowest electrical resistance value among corroded cables, with a value of 1.4 Ω, corresponds to the cable that was in the air and cuprite (Cu2O) was formed on its surface. The cable that was placed in the water environment showed a resistance of 1.8 Ω.

Table 4 shows the results of the data transmission speed test in the studied cables. The cable corroded in water with greater electrical resistance against the movement of electrical charge carriers shows a lower value of data transmission speed. The results of measuring the speed of the data are in good agreement with the results of the evaluation of the electrical resistance and the band gap value of the compounds caused by corrosion. Also, the results of Table 4 show that the signal-to-noise ratio is higher in the cable corroded in the air. It seems that the combination of two corrosion products in the water environment, which includes cuprite and malachite, has led to more disruption in the process of data transmission and the absorption of unwanted environmental signals.

4. CONCLUSION

Due to the corrosion of copper cables underground and in the vicinity of the soil, a surface layer of copper oxide II (CuO) is formed on the cable. The formation of this copper oxide causes a decrease in the lattice distances of atoms and as a result disrupts the transfer and mobility of electric charge carriers. Therefore, due to the presence of CuO and the decrease in the mobility of charge carriers as well as the decrease in the effective cross-section of the cable for the passage of current, the electrical resistance in the corroded cable has increased and this leads to a decrease of about 30% in the speed of telecommunication data transmission through the cable. Due to the corrosion of copper cables in the water and air, different surface layers are formed on the copper surface. In both cases, one of the corrosion products is cuprite, but malachite is also formed in water. In general, the cable corroded in water shows higher electrical resistance and lower data transmission speed along with a weaker signal-to-noise ratio. The cause of this behavior was related to the amount of band gap and the appearance of sediments. The band gap of malachite is significantly higher than that of cuprite. Therefore, a lower electrical conductivity is expected from malachite. Also, the simultaneous formation of cuprite and malachite in the cable corroded in water leads to more noise and disruption in the data transmission process.

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