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by

I. C. MacFARLANE

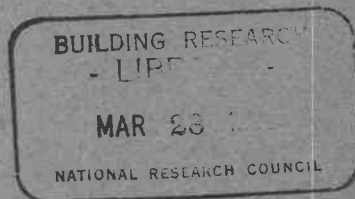ANALYZED

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THE CORROSIVENESS OF MUSKEG WATERS: A REVIEW

I. C. MacFARLANE*

ABSTRACT

Muskeg waters are generally acidic and potentially corrosive to concrete and metal structures. The amount of dissolved salts and free carbon dioxide in the water is an important factor in its aggressive attack on concrete. Although pH measurements are not the only criterion of aggressiveness, they are a reasonable indication in many instances of potential severity. A good defence against an aggressive environment is a high quality, very dense concrete. High alumina concrete and air-entraining agencies provide further protection in extremely aggressive environments. Surface treatments of concrete have not proved to be very successful over a long period of time.

Corrosion of metals in a muskeg environment is an electrochemical action; the type and rate of corrosion are functions of the property of the metal as well as the soil and water conditions. Factors such as dissolved salts, pH, total acidity, resistivity, aeration, and presence of anaerobic bacteria influence corrosion. Optimum protection to metals in an aggressive environment is provided by a combination of a surface coating and cathodic protection.

SOMMAIRE

Les eaux de muskeg sont généralement acides et peuvent être corrosives pour les ouvrages de métal et de béton. La quantité de sel dissous et d'anhydride carbonique libre dans l'eau est un facteur important dans son agressivité contre le béton. Quoique les mesures de pH ne constituent pas les seuls critères d'agressivité elles fournissent une indication raisonnable dans de nombreux cas de dommages possibles. Une bonne défense contre un environnement agressif est un béton très dense et de bonne qualité. Les bétons à haute teneur d'alumine et les ingrédients d'entraînement de l'air fournissent une protection supplémentaire dans des milieux extrêmement agressifs. Les traitements de surface du béton n'ont pas donné de très bons résultats à long terme.

La corrosion des métaux dans les eaux de muskeg provient d'une action électrochimique ; le type et la vitesse de la corrosion sont fonctions de la propriété du métal ainsi que des conditions du sol et de l'eau. Les facteurs tels que les sels dissous, le pH, l'acidité totale, la résistivité, l'aération, et la présence de bactéries anaérobies influencent la corrosion. La protection optimum pour les métaux dans un milieu agressif est fournie par un revêtement de surface et par une protection cathodique.

Increased construction activities in Northern Canada have intensified interest in the effect on various structures of the water that is always encountered in muskeg. Potential corrosion is a matter of considerable economic significance due both to this increased pace of construction in the North and to the increasing costs of maintaining or replacing damaged structures. Concern has been expressed for both concrete and metal (particularly steel) structures. Questions being raised include: do muskeg waters have a deleterious effect on concrete and steel; if so, how serious is it; and what protective measures should be taken? This paper will attempt to answer these questions, based on a study of the available literature.

The interest of the Division of Building Research in the subject of corrosiveness of muskeg waters was stimulated several years ago by an inquiry regarding the effect of muskeg waters on concrete. A literature survey was made and the subsequent report published in the proceedings of one of the annual Muskeg

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Research Conferences sponsored by the Associate Committee on Soil and Snow Mechanics of the National Research Council (MacFarlane, 1961).

Most of the available information on the effect of muskeg waters on concrete is based on investigations carried out in the United States and the United Kingdom, and to a lesser extent in continental Europe, on the performance of concrete drain tile and other structures in peaty waters. No active research of this type is known to have been carried out in Canada. There is no reason to doubt that the conclusions reached about the effects of peat bog waters in other countries do not apply equally well to the muskeg waters in Canada. Rather more information on Canadian experience is available on the effect of muskeg waters on metal structures, with interest centred on pipelines, culverts, and electrical transmission towers.

THE NATURE OF MUSKEG WATERS

Waters from areas where there is a considerable accumulation of peat tend to have an acid reaction. In some muskeg areas, however, organic acids arising from the decay of peat are neutralized by the lime in the soil (Lea, 1936, 1956). Peats occurring in such areas may contain pyrites and marcasite and oxidation of these iron sulphides would lead to the production of free sulphuric acid (Alway, 1922; Stewart, 1922). This is often neutralized by the bases present in the soil, giving sulphate salts, but in some cases the production of acid may be sufficient for free sulphuric acid to occur in the ground water.

It is more common, however, for muskeg areas to be almost free of dissolved salts, although acidic owing to the presence of carbon dioxide and humic acid arising from the decay of the peat. Some of the simpler organic acids such as acetic acid may also be produced in small quantities. A saturated solution of humic acid in water has a pH of 3.6 to 4.1, the strength of this acid lying between that of carbonic and acetic acids. The quantity of free humic acid that can be carried in water is small owing to its low solubility. Peaty waters, which are practically free of salts, generally show pH values between 4 and 7 (Lea, 1956). It has been suggested that the acidity of peaty waters fluctuates with the season and weather (Lea, 1956), being greatest after a heavy rain following a warm dry period. Other investigators found no such correlation between acidity and season, but suggest that the dominating factor is the stage of succession of a bog (Thompson, Lorah and Rigg, 1927) or the degree of decomposition of the peat (Elliot, 1923). It is probable that all these factors, together with many others, influence the acidity of peat and peaty waters.

The impression must not be given that muskeg waters are always acidic. This is not the case. An investigation of the pH and calcium content of drainage water from some peat deposits in New York (Wilson et al., 1932) indicated that the relative acidity of the upper layers of a deposit and the pH of the drainage water from the upper few feet of the soil will probably be determined, to some degree at least, by whether the deposit rests on a calcareous or non-calcareous material. Drainage water from relatively shallow peat deposits underlain by a calcareous material will probably contain comparatively large quantities of calcium and consequently would not be particularly aggressive to concrete, although it may be aggressive to metals.

In many large areas of Northern Canada, for example in the vicinity of Fort Churchill, peat is alkaline rather than acidic in reaction (Radforth, 1955). Due to flooding conditions, which often occur in some of the muskegs at least once a year, dissolved materials are brought up into the organic material from the mineral soil below, thereby charging the peat with agents that are frequently alkaline in reaction. Where plateaux of peat occur (rather extensive areas of peat of a higher elevation than normal terrain level) the top portion is often acidic (pH 5–7) and the bottom, alkaline (pH 8.0–8.5). Where the terrain is flat and poorly drained, the pH of all the peaty material is frequently alkaline (pH 8); where it is even and the drainage better, the reaction may be predominantly acidic (pH 4–7).

Many muskeg waters have a characteristic brownish colour. There appears to be only a very indefinite relationship between the colour of this water and its acidity (Thompson *et al.*, 1927), although the intensity of colour seems to increase with an increase in acidity. The colour is rather more closely correlated with the stage of plant succession; the later the stage, the more intense is the colour of the water.

CORROSION OF CONCRETE

1. *Principles of Corrosion*

Deterioration of concrete by the action of aggressive waters is a chemical action. Pure water will decompose hardened cement compounds, dissolving the lime from them and to some extent the alumina (Lea, 1956). This action on a mortar or concrete is generally so slow that it is negligible unless water is able to pass continuously through the mass. Waters that are acidic owing to the presence of uncombined carbon dioxide and organic or inorganic acids are more aggressive in their action, the degree and rate tending to increase as the acidity increases. Acid solutions that attack cement mortars or concrete by dissolving part of the set cement progressively weaken the material by removal of the cementing constituents.

In an investigation into the corrosive effect of acid waters on concrete laboratory specimens (Tremper, 1931), it was found that when about 50 per cent of the original lime had been removed from an average concrete, complete loss of strength and coherence resulted. Investigations in Scotland (Halcrow, Brook, and Preston, 1928) and in Scandinavia (Hellstrom, 1933) have shown that aggressive peaty waters percolating through a fairly permeable mass concrete structure will dissolve the lime and calcium aluminate in the cement. Although the degree of attack on these mass concrete structures would not be sufficient to affect their stability, the same degree of attack may be sufficient to destroy a concrete pipe with a wall thickness of only 1 or 2 inches. Masses of permeable concrete have been completely destroyed in 5 years, however, by peaty waters of pH 6.5 combined with wave action (Walsh, 1933).

One particularly interesting example of the effect of peaty water on a mass concrete structure occurred in Scotland (Halcrow, 1934). The Blackwater Dam of the Kinlochleven works of the British Aluminium Company was thoroughly investigated some twenty-five years after it had been built. Wherever seepage through the dam had occurred, a deposit of lime in the form of $CaCO_3$ had accumulated on the downstream face; this deposit varied in thickness from a

mere wash of lime to a crust 3 inches thick. From analyses of the seepage water and of core samples of the concrete, it was estimated that in 25 years some $52\frac{1}{2}$ tons of free lime had been washed out, the equivalent of a loss of 85 tons of cement out of the 40 thousand tons used in the construction of the dam.

Pure water will dissolve lime to an extent of about 1.2 gm/litre (Lea, 1956). As has already been pointed out, carbon dioxide present in water in a free state increases the aggressive action of the water. Initially, it reacts with lime to form insoluble calcium carbonate, but on further action the much more insoluble calcium bicarbonate (temporary hardness) is formed. A solution of calcium bicarbonate alone in water will not dissolve further quantities of calcium carbonate, and if it reacts with lime the insoluble calcium carbonate is formed. A certain amount of free carbon dioxide is also required to stabilize calcium bicarbonate in solution so that not all of it is available to attack concrete. Waters that contain only combined carbon dioxide present as carbonates or bicarbonates have, therefore, no appreciable solvent action. It is only when the water is very pure or contains free carbon dioxide and acids that it will attack set cements.

2. *Prediction of Corrosion Due to Muskeg Waters*

Prediction as to whether or not an environment is potentially corrosive to a concrete structure is not simply a matter of determining the pH of the water. The degree of acidity does not give a simple measure of the aggressive action, although it does bear some relation to it. In addition to pH measurements, an analysis of the water would be informative, especially with regard to free CO_2. It is important to be reminded also that corrosion is a function of the quality of the concrete. Deterioration of concrete depends a great deal on the permeability of the cement paste; this in turn is related to the water-cement ratio as well as to the compaction of the mix (Powers *et al.*, 1959).

Considerable information is available on the relation of pH to corrosiveness. A laboratory and field investigation of concrete tile installed in peat carried out at the University of Washington (Elliot, 1923) has shown that although an acid subsoil contributes to the disintegration of tile, a high percentage of lime, and even the presence of marl, is no guarantee against corrosion. Other tests (Tremper, 1931) on a large number of concrete laboratory specimens in artificially acidified water showed that for the range of acidity expressed by pH values between 6.0 and 7.0 the degree of attack was inversely proportional to the pH number. Above pH 7.0 attack was negligible. Waters of high velocity tended to accelerate the rate of attack.

A series of laboratory tests in Sweden on concrete pipes subjected to an acid environment (Werner and Giertz-Hedstrom, 1934) also indicated that the aggressive action of the water increased with increasing degree of acidity.

A comprehensive investigation extending over twenty-four years was carried out at the University of Minnesota (Miller and Manson, 1948); it showed that in general the degree of corrosion of concrete specimens varied with the acidity of the peat and with the unit strength of the concrete in the test specimen when installed in the peat. Poor-quality concrete tile did not give satisfactory service even in low acidity peats with a pH of 6.0 or higher. Strength is related to the

water-cement ratio, which determines the permeability in high strength concrete that gives the resistance to attack.

An assessment of the problems involved in the selection of culverts for muskeg areas (Brawner, 1962) has shown that concrete culverts may have a life expectancy of anywhere from 10 to 30 years, depending upon the rate of deterioration. The suggestion is presented that the rate of attack can be estimated from a measure of the pH and soil resistivity.

The temporary hardness of the muskeg water, together with its pH, may also be used to predict its aggressiveness to concrete. As a broad guide, a water with a temporary hardness of 10 to 20 ppm will not have a marked solvent action unless the free carbon dioxide is above 10 ppm (Lea, 1956). For a temporary hardness of 5 ppm the corresponding free carbon dioxide is 5 ppm, whereas water with a temporary hardness of less than 2.5 ppm can be aggressive even if the free carbon dioxide is negligible. Water may be aggressive for pH values up to 7.0 or even 7.5 if the temporary hardness is less than 2.5 ppm, and at pH values up to 6.0 to 6.5 for higher values of temporary hardness.

3. *Protective Measures*

It will already have been made clear that in order to resist attack by aggressive waters, concrete must be of high quality and dense, i.e. of low permeability and high strength. Other protective measures such as special cements and special admixtures have also been investigated and may be required under certain conditions.

In the Scottish study already referred to (Halcrow, Brook, and Preston, 1928) a series of experiments was carried out on some 113 different materials consisting of varying mixtures of Portland, slag and aluminous cement concretes, and surface treatments of tars, bitumen, bricks, renderings, and chemical treatment. After subjecting the materials to moorland water over a long period of time, it was concluded that the surface treatments had a life of only 4 to 5 years, which was hardly adequate. Of the few concretes unaffected after a period of several years those made with aluminous cements were outstandingly good. A similar conclusion regarding the efficacy of high alumina cements for concrete in an acidic environment was reached at the University of Minnesota (Miller and Manson, 1948a), where investigations indicated that rich mixes of high strength and low permeability provided very good resistance to soil acids.

An example of the use of high alumina cement concrete to counter corrosive effects of peat may be seen in the piles for the grade separation structures of the Burnaby Expressway in British Columbia (Heavy Construction News, 1961) where study had indicated that the peaty waters were potentially very corrosive. High alumina cement precast concrete piles were used rather than steel piles or ordinary Portland cement concrete piles with a special surface treatment.

With regard to surface coatings, Tremper (1931) also found that they generally reduced the rate of attack for only about two years, the performance of such protection depending upon the durability of the coating or the frequency of its renewal. Tremper also commented on the marked improvement in the resistance of high-quality Portland cement concrete over poor-quality concrete.

A series of laboratory investigations in South Africa (van Aardt, 1955)

showed that "green" concrete is much more vulnerable to aggressive agents in water or soil than is well matured concrete; consequently, in some instances it may be necessary to provide special curing. It was concluded from this study that wherever concrete is to be subjected to an aggressive environment, a well designed plastic mix with a low water-cement ratio should be used, with care taken to obtain full compaction and ensure low permeability.

In a search for cheaper alternatives to the usual expensive physical (e.g., painting of surfaces) and chemical (e.g., use of high alumina and waterproof cements) methods of protecting concrete from peaty waters, a series of tests was carried out at the Gaur Project in northern Scotland (Fraser, 1955). The pH of the run-off in this area is sometimes as low as 4.0. Three types of concrete were tested: ordinary Portland cement concrete, Portland cement concrete with an air-entraining agent for improved physical resistance, and Portland cement concrete with a minute quantity of water softener for improved chemical resistance. It was found that the air-entrained concrete behaved more consistently than either of the other two, and it was recommended for all concretes exposed to acid water attack. This confirms Brawner's view (1962) that high-density concrete and air entrainment should be specified for concrete structures in muskeg areas.

CORROSION OF METALS

1. *Principles of Corrosion*

In all cases of corrosion in the presence of moisture, the mechanism of corrosion action is electrochemical. The three essential requirements for corrosion are an electrically conducting structure or metal, an electrolyte, and some mechanism whereby potential differences are self-generated on the metal (Mainland, 1962). The electrochemical principles upon which the theory of the mechanism of corrosion is based are fairly simple, although their application is apparently complex. The theory very briefly and simply stated, is that a difference in electrical potential causes a flow of electrons from the point where the metal ions go into solution (the anode) through the metal to the area where the hydrogen ions congregate (the cathode). At the same time, a transfer of ions takes place from the anode through the soil water (the electrolyte) to the cathode (Scott, 1960). Factors that influence corrosion in soil are related to the properties of the metal, the soil and the water. It is the last two with which this paper is primarily concerned.

Soil and water factors that affect type and rate of corrosion include physical properties of the soil (e.g., void ratio, permeability), chemical properties (soluble salts in the soil and water, pH, and total acidity), resistivity (electrical resistance of the soil), aeration (availability of oxygen), and the presence of micro-organisms. Permeability of the soil affects the rate of corrosion in two ways: it controls the rate of diffusion of the corrosion products and the rate at which oxygen can reach the corroding metal. A change in texture or structure of the soil surrounding two parts of the same section of metal will change the amount of water, air, and dissolved oxygen in contact with it and may result in a potential difference between the two parts—an oxygen concentration cell. This can lead to significant corrosion when a structure, for example, is partly in an inorganic soil and partly in peat.

Low electrical resistivity and relatively high quantities of soluble salts generally indicate high corrosivity. An acid soil would also be expected to be corrosive because of the tendency to prevent the formation of protective films.

Oxygen, either from the atmosphere or from oxidizing salts or compounds, tends to stimulate corrosion. Local variations in the supply of oxygen to the soil surrounding the metal can set up oxygen concentration cells (Brawner, 1962). Such cells often result in corrosion on the under side of a culvert or pipeline.

The micro-organisms found associated with soil corrosion are sulphate-reducing bacteria, which occur under anaerobic conditions. These thrive in the absence of oxygen and in environments that are fairly neutral or slightly acid, for example, pH 6–9. These bacteria are believed to be common in muskeg areas.

Corrosion of metals involves other factors interrelated to each other and to the factors mentioned above. The relationship is rather complex, however, and present knowledge is not sufficient to determine precisely how corrosive a particular environment will be. Nevertheless, it is usually possible to make some differentiation between mildly corrosive and severely corrosive conditions.

2. *Prediction of Corrosion in Muskeg*

A potentially corrosive environment will be one that is poorly drained, has soils high in organic content and dissolved salts, is low in resistivity, is high in total acidity, and favourable to differential aeration and anaerobic bacteria. Methods for estimating the soil corrosiveness usually entail the measurement of one or several of these factors. The water in close contact with soils of this nature will probably have much the same properties as the parent material (except, perhaps, for run-off diluted by surface water) and therefore will be potentially corrosive.

A common indicator of soil corrosiveness is soil resistivity; Table I is often used as a guide (Mainland, 1962).

TABLE I

0	to	1,000 ohm-cm	Severely corrosive
1,000	to	10,000 ohm-cm	Moderate to severe
10,000	to	100,000 ohm-cm	Very moderate
100,000 ohm-cm and over			Non-corrosive

Resistivity readings taken in peat in the vicinity of a proposed structure, together with an assessment of the over-all drainage pattern, muskeg type, and other features, may indicate whether further information should be obtained from the drainage water itself (if the structure is to be subjected to water attack only). Economic considerations will dictate whether it will be advisable to supply such detailed information as resistivity, soluble salts, pH, total acidity, available oxygen, and presence of micro-organisms.

From a consideration of the effects of the various factors noted above on the rate of corrosion, it may generally be predicted (Mainland, 1962) that:

(a) corrosion should be fairly slow and of a uniform nature if a structure is to be entirely immersed in a large body of muskeg;

(*b*) some corrosion can be expected due to differential aeration cells if it is to be only partly immersed;

(*c*) the corrosion rate in the metal will be appreciably increased if sulphate-reducing or other types of depolarizing bacteria are present in the peat;

(*d*) there will be very serious corrosion in a structure near the edge of the muskeg if it is a long one (such as a pipeline) and buried in peat and adjacent inorganic soil.

3. *Protective Measures*

Basically, there are two solutions to the problem of corrosion of metal structures immersed in peat or subjected to peaty waters: coating and cathodic protection.

The most common method of protecting steel is to galvanize it. The main feature of the galvanizing is the anodic nature of zinc when in contact with steel and this prevents pitting of the steel. Brawner (1962) reports that galvanized metal in highly acid soils will probably lose the zinc coating in only 2 to 4 years. For the particular case of culverts, if the water flowing through them has a high total acidity, their life cannot be increased significantly by galvanizing alone. Brawner suggests an additional protection in the form of an asphalt coat about 50 mils thick, but extreme care must be taken to ensure that it will adhere to the zinc.

The experience of the Hydro-Electric Power Commission of Ontario with galvanized steel transmission towers in muskeg is of particular interest. An investigation (HEPCO, 1961) of transmission towers built from 25 to 40 years ago showed that when the foundations had been carefully backfilled with peat no appreciable corrosion occurred. On the other hand, foundations left without backfill and with galvanized members in direct contact with the peaty ground water (the level of which fluctuated with the season) showed serious attack. Their conclusion, therefore, was that with careful backfilling special coatings other than galvanizing are not warranted.

Special coatings, if required, should be selected on the basis of their water resistance. For pipelines in muskeg, as well as for smaller-diameter culverts, normal pipeline enamel, plastic tapes, and coal tar epoxy paints are generally satisfactory (Mainland, 1962), but it is essential that the coating is applied to the entire structure.

For cathodic protection of buried steel the normal criterion is that the metal-to-soil potential should be maintained at a value of -0.85 volts with respect to a copper sulphate electrode (Mainland, 1962). The output of the cathodic protection system will have to be adjusted so that the entire structure will achieve this potential or be even more negative. The presence of sulphate-reducing bacteria will necessitate an increase in the potential to -0.95 volts. Protective current densities on the metal should be about 2 to 3 ma/ft.^{2} in the absence of bacteria or 6 to 7 ma/ft.^{2} if bacteria are present. Cathodic protection, however, is normally considered only in conjunction with a protective covering and a good coating will reduce current requirements by a factor of about 100. This combination of a coating and cathodic protection will provide the optimum protection.

SUMMARY

1. Muskeg waters are usually acidic in reaction and are potentially corrosive to concrete and metals. Waters of an alkaline reaction may also be corrosive.

2. The hydrogen-ion concentration, or pH, alone is not the only criterion of the aggressiveness of muskeg waters to concrete. Of equal importance are the amount of dissolved salts and the free carbon dioxide in the water. Soft waters can be highly aggressive to concrete even if the acidity is low. Nevertheless, a low pH value would give some indication of potential aggressiveness to concrete and appropriate precautions should be taken.

3. Colour of muskeg water is not necessarily a good indication of its potential aggressiveness.

4. Running water is potentially more harmful than stagnant water. Further, attack at a constantly changing water level is stronger than attack on a completely immersed structure.

5. Thin-walled concrete structures such as drain tile and culverts are much more susceptible to aggressive action than are mass concrete structures.

6. Fresh concrete is more susceptible to attack than mature concrete. Consequently, precast concrete will probably be more resistant to an aggressive environment than cast-in-place concrete.

7. The more dense and impermeable the concrete, the greater will be its resistance to attack.

8. High alumina cements, as well as air-entraining agents introduced into the concrete, have been demonstrated to be effective in countering aggressive attack.

9. Many surface treatments have a life considerably less than the design life of the structure, and generally have not been satisfactory over a long period of time.

10. The quality and quantity of impurities in muskeg waters affect the corrosion of metals inasmuch as they influence acidity, resistivity, aeration, and the presence of anaerobic bacteria.

11. Measurements of pH and resistivity give a reasonable estimate of the corrosiveness of an environment.

12. Measures for countering the effect of an aggressive environment on metals include coating and cathodic protection. Galvanizing of steel is usually adequate, except where the structure is subjected to running water or to a fluctuating water level. Under such circumstances it may be necessary to add a waterproof coating or to apply cathodic protection. Optimum protection is provided by a combination of a coating and cathodic protection.

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