

Pole Preservation Through Alteration of Wood Rot Microbial Community Activity

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Abstract

Most current methods for the preservation of wood structures in the environment are based on the treatment of the wood itself with toxic materials to prevent the colonization and decay of wood by insects and microorganisms. We present the concepts and test data relative to using a different approach to prolong the life of wood structures. This approach involves treating the soil adjacent to the structure to retard the growth and decay activity of wood rot organism. Most wood decay is due to the metabolic activity of aerobic bacteria and fungi, and insects that are also obligate aerobes. If the environment around the base of the pole can be made anaerobic, decay processes should be at a significantly slower rate. Rates of oxygen diffusion into the soil environment occur under a number of different ground line conditions are modeled. This demonstrates the potential for significantly increasing the fraction of time during which anaerobic conditions prevail and decay is slower. These calculations suggest prolonging the life of the wood structure by at least half. Preliminary laboratory and field test data is presented which suggests that the TRILAB³ treatment approach does protect wood structures from decay beyond that achieved by pole treatment alone.

Introduction

Basic Wood Decay Principles

Since earliest recorded history the use of wood for structures, implements, and heat has been intimately involved in the development of man and his culture. The unique properties of wood, including its wide availability, variety of different forms, ease of machining in many ways, and renewability make it ideal for myriad applications. Since wood has existed on earth for well over a billion years microbial communities have had ample

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time to evolve enzymatic mechanisms to break down and utilize the components of wood. While many creatures may consume wood, only bacteria and fungi have the enzymes responsible for its decomposition.

For wood structures in the environment in general, and poles and pilings in particular, decay results from the activity of three major groups of organisms (3). Bacteria of many genera have the ability to utilize the cellulose and hemi-cellulose components of the wood, generally using the material to support the reproduction and growth of the microbes. Filamentous fungi are major wood degraders with their hyphae being important in penetration of wood fibers. Finally, wood boring insects and insect larvae also participate in wood degradation. The bacteria are probably most important in cellulose breakdown, with the fungi, particularly the Basidiomycetes, responsible for most lignin decomposition. The rigidity and structural integrity of wood is dependent on maintaining the lignin backbone and supporting cellulose materials. Almost all the organisms important in these processes are aerobes, most obligately aerobic (4). Among the most compelling evidence that wood decay is biologically mediated is the experience with wood structures in the environment. Properly treated utility poles, marine pilings, deck support timbers, etc. usually fail at or near ground or water level. The rot is fastest and most extensive where oxygen and moisture exist creating conditions conducive to the metabolic activity and growth of aerobic microorganisms, like bacteria and fungi. As the number of organisms and their metabolic processes increase the decay of the wood also increases.

For a very long time man has looked for ways to treat wood that retard decay processes. If we start with the premise that decay is inevitable, then our goal is to delay the onset or slow the progress of the decomposition process. Current technology has been based almost entirely on treating the wood with materials toxic to the bacteria, fungi, and insects. While this strategy has been quite effective, if done properly, it has led to potential environmental problems at the individual poles, and major hazardous waste problems at the wood treating sites.

In addition to inhibiting microorganisms and insects most of the chemicals also are toxins or carcinogens for humans and other animals. All of the major wood treating materials currently used, i.e. creosote, pentachlorophenol, and CCA, represent human and environmental health hazards. Currently EPA lists over 3,000 current and former wood treating operations as hazardous waste sites. The clean up of these sites represents a major liability for the wood treating industry and railroads, as well as society in general.

Characteristics of Soil

Microbial metabolism is most rapid under conditions where oxygen is available to serve as an electron acceptor. The amount of energy available to an aerobe is approximately 19 times that which can be extracted by anaerobes from the same food materials. It is well known that the rates of microbially mediated processes are many times slower in the absence of oxygen (3). This will be especially true of wood decay organisms because of the unique nature of wood and its constituents. Since it is a complex polymer, cellulose, like almost all polymers, is slowly degraded anaerobically. It is degraded, however, witness the anaerobic digestion of cellulose in the cow's rumen, mediated by a unique group of anaerobic cellulose fermenters. The major structural component of wood, lignin, is degraded primarily by fungi, particularly basidiomycetes, which are all obligate aerobes. One of the few generalizations that have appeared is that lignin and aliphatic hydrocarbons do not degrade anaerobically (3; 11). A detailed review of anaerobic degradation of lignin suggests it may be biochemically possible, but is very rare in nature (4).

In most soils there are a mix of aerobic and anaerobic microhabitats. The relative mix of the two is dictated by a wide variety of factors that will be discussed below. In soils where conditions favor more anaerobic conditions (wet, high clay soils for example) organic materials, like wood tend to rot less rapidly. Figure 1 shows an example of gas dynamics in soil (10). Oxygen decreases with depth, essentially disappearing in the first 10

meters of the soil column. The gradient of oxygen depletion can be much more dramatic near the surface of soil particles where oxygen disappears within only a few millimeters (9). This disappearance is driven by several factors and influenced by several more. Since the major focus of our work is controlling the availability of oxygen in soil as a means to control wood rot, it is worthwhile to look at these processes in some detail. Oxygen availability is regulated by two factors, *oxygen concentration* and the *flux rate* at which it moves through the soil. Oxygen concentration is a function of atmospheric composition and processes that consume oxygen. The data in Figure 1 shows that oxygen (given in mole fraction, X_i) is quite rapidly depleted due to microbial utilization for the oxidation of natural organic matter, including, but not limited to that added to the soil annually from above ground plant production, and methane from below. Additionally, there are reactions of oxygen with mineral constituents of soil. The oxygen flux rate can be calculated using Fick's Law and produces a very high and probably useless value for potential oxygen flux. The reason the calculated value is useless rests on the fact that real soils violate most of the assumptions necessary to make the calculation. Measured values are usually much less than the calculations would predict. There is general agreement on the factors that are important determinants or modifiers of the rates of oxygen flux, but little consensus on how they should be measured or what values to use. We are still at the stage where each site and soil must be considered on a site specific basis.

Table 1 summarizes the factors that may effect oxygen flux rates and identifies the mechanisms and magnitude of the effects. Probably the dominant factor, in most instances, is the amount of moisture present. The diffusivity of oxygen through water is approximately four orders of magnitude slower than through air. In most dry, aerobic soils the processes that consume oxygen are never rapid enough to counteract the rate of diffusive transport into the soil, at least in the top 10 meters. This situation very rarely exists, however, since

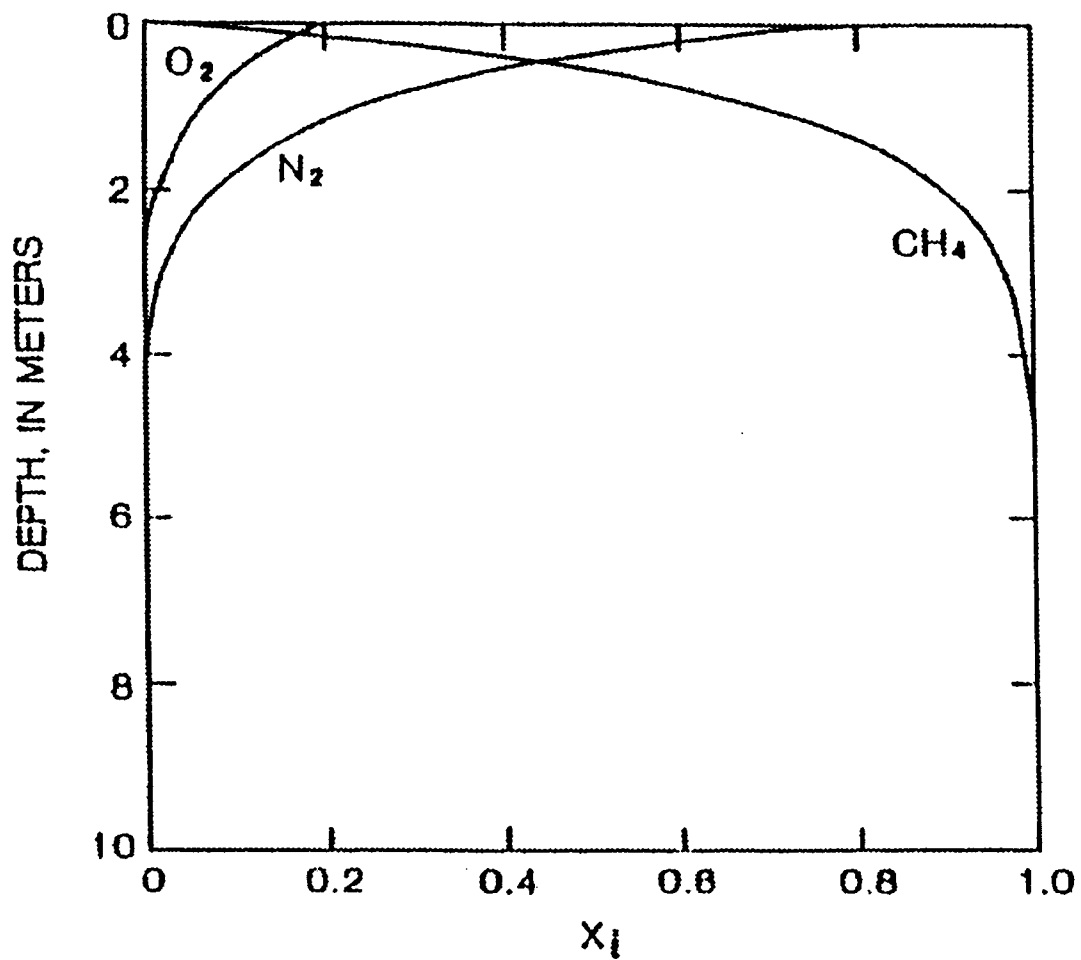


Figure 1. Gas Dynamics in Soils With Depth (10).

completely dry soil is very rare. The presence of even a small amount of moisture (15% relative humidity, as below this value there is very little biological oxygen demand (5)) will coat the soil particles, decreasing the inter-particle air spaces, binding soil particles together. Eventually we reach saturated conditions at relative humidities greater than 85%. The significant range is therefore 15-85% relative humidity, below which there is little oxygen demand and rapid transport, and above which conditions are saturated and oxygen/water flux rates are operative.

Other important factors (Table 1) include particle size of the soil which impacts porosity or the size of the holes through which gases move. The smaller the particles the slower the movement of soil gases and the greater effect of water filling intra-particle spaces which eventually leads to oxygen depletion. The effective pore sizes range from $0.6 V_{\text{voids}}/V_{\text{solids}}$ for sand to $0.3 V/V$ for clay soil. Organic carbon and the microbes that degrade it create an oxygen demand, the nature and magnitude of which will depend on a number of factors, including soil texture, moisture, plant communities in the overlying soil and temperature. Organic carbon can also significantly change the properties of soil by coating the surface of mineral particles which can decrease soil pore space and further decrease oxygen transport. At organic carbon concentrations over 0.5% most particles are completely coated. The particle sizes associated with a particular soil not only constitute surfaces with which the gases interact but dictate the pore sizes through which transport must occur. The range is from large particles (sand) which leave large spaces through which air can move, to small particles (clay) producing soils that tend to waterlog and become anaerobic. As suggested previously, although it is commonly recognized that these and perhaps other factors are important there is little agreement on what values to attach to each for a particular soil. In most instances we do not have sufficient data available on a particular soil to make estimates. Further complicating the picture is the seasonal, and sometimes daily variability in each of these factors. Many workers have suggested that viscous fluxes driven by changes in atmospheric pressure may be much more significant over short time intervals than any of these diffusive fluxes, although there is little work available on how to model or

evaluate these pressure driven changes.

Table 1. Summary of soil properties impacting oxygen availability. Oxygen flux rate oxygen/air= 7.0×10^{-8} moles/cm²/sec; oxygen/water= 4×10^{-12} moles/cm²/sec

Property	Mechanism of Effect	Range of Values
Moisture	Impacts pore size, flux rate	15-85% Relative humidity
Temperature	Regulates reaction rates	Little activity below 10°C
Organic Carbon Content	O ₂ Demand, particle coating	0.2 - 15%
Soil Texture, Porosity	Pore size V_{voids}/V_{solids}	0.3 - 0.6
Tortuosity	Path length of O ₂ diffusion	0.8 - 0.95

A New Approach to Protecting Wood Structures

Clearly, the soil in which we place wood structures of all kinds is a highly complex and variable environment. The organisms responsible for the decay of wood are subject to all the complexity and variability. The one common requirement for wood decay is oxygen and another is water. Most previous attempts to control wood decay have been based on treatments of the poles to prevent their colonization by insects and microorganisms. That level of protection seems to be essential for a pole to have an economically realistic lifetime. However, the lifetime of those treated poles may be extended, perhaps quite significantly, by changing conditions in the soil environment around the pole to make it less conducive to wood rot organisms. If an oxygen demand can be added to the soil surrounding the pole it is possible to create anaerobic conditions. For the fraction of time these conditions can be maintained, wood decay will be at the anaerobic rate, which is many times slower than the aerobic rate. In addition, under anaerobic conditions sulfate is reduced to hydrogen sulfide quite rapidly and in high concentrations (2). Hydrogen sulfide is toxic to most soil invertebrates. Critical to this process is the amount and form of water in the soil since it will largely control the oxygen flux rates. The

following points must be considered in developing this approach:

1. It is impossible in a natural setting to prevent rot completely, no matter how hard we try. It is also impossible to maintain anaerobic conditions around the pole at all times. For some fraction of the time rates of oxygen flux into the pole environment are dominated by oxygen/air interactions and likely to be too fast to maintain anaerobiosis no matter what the oxygen demand of added materials. In these cases the rates of utilization are slower than the rates of oxygen diffusion. For most parts of the country this is a very small fraction of the time, mainly when conditions are very dry. Fortunately, dry conditions are not conducive to active decay because microbial activity ceases at soil relative humidity less than 15% for most bacteria (7), and 50% for fungi (6), with significant declines in activity at less than 85%. The area of observed rot is near the soil surface where rates of oxygen diffusion will be higher than at depth. Most soils have very little free oxygen at depths below 1 meter (10).
2. Wood decay does not occur at all times when moisture is available. During part of the year, a significant part in some areas, the temperature is too cold for active microbial activity. This temperature will vary with location and other soil conditions, but in the southeast aerobic microbial metabolic activity profoundly declines below 10° C (8).
3. When the soil is waterlogged oxygen diffusion is controlled by air/water flux which is much slower than oxygen/air flux rate. Microbial utilization of natural carbon compounds and abiotic oxidation reactions can reduce oxygen levels to near zero, although the rates may be slow enough that it takes several days to establish anaerobic conditions, and they may not persist long, especially near the soil surface where drainage and oxygen diffusion will be most rapid. The addition of oxygen demand under saturated conditions can hasten establishment of anaerobiosis and maintain it longer so that a greater fraction of the time will be under the slower anaerobic decay conditions.

4. Oxygen flux through partially saturated soil will depend on all the factors listed in Table 1 and vary significantly from soil to soil. It is likely that addition of oxygen demanding materials can create anaerobiosis for some of this time. For example, modeling of soil gas fluxes suggests that natural oxygen demanding processes decrease the flux by approximately 40% at 0.5 meters depth (10). Other workers suggest an even greater utilization, perhaps as much as 80% (9). Some fraction of the pore space in any soil will be occupied by water either in a boundary layer around soil particles or actually filling the pore space which decreases the effective flux rate of oxygen. As noted above there is a direct relationship between microbial activity and moisture levels. Maximum rates are at 95-99% relative humidity and little below 85% (7). At 85% relative humidity only about 15% of the pore spaces contain air. Soil organic carbon (SOC), mostly complex humics, are large molecules that persist for long periods. Even at SOC levels as low as 0.5% most of the particles are coated with organic carbon which, among other things, acts as a glue to cement soil aggregates together (5). Oxygen diffuses poorly or not at all through such aggregates. The numerical value is in significant doubt but is probably around half of the available space.

$$O_2 \text{ Flux} = \text{Fraction Utilized (Fu)} \times \text{Fraction of pore space available water (Fps)} \times \text{fraction pore carbon (Foc)}$$

$$O_2 \text{ Flux} = Fu (1 - .40) \times Fps (1 - .85) \times Foc (0.5) = 0.045$$

This example suggests that oxygen flux is only about 4.5% of that in a dry inorganic soil. It is likely that additional oxygen demand could maintain anaerobiosis under these conditions of oxygen flux.

Since our goal is to extend the useful life of wood structures, like utility poles, and the way to use natural processes to do this is to extend the fraction of the time the soil around the poles is anaerobic, let's extend the above example to compare the number of low rot days per year under natural conditions to those with added oxygen demand conditions. Our assumptions are based on soil (sandy loam) and climatic conditions with which we are familiar, i.e. those in the mid-Atlantic region of the southeast. The outcome would not be dramatically

different in most of the U.S. east of the Mississippi. Table 2 presents the comparison.

Under both scenarios there are times when climatic conditions are not appropriate for active decay. Under water saturated conditions soil amendments can have the most dramatic effect by using up the oxygen present, and creating and maintaining anaerobic conditions. These may also be the days of most active decay since the high moisture conditions would favor higher rates of microbial metabolism. The most uncertain conditions are those highly variable times when some oxygen is present and some moisture. There is very little data available on which to base conclusions. The major factor in determining how many days added protection can be achieved is how fast oxygen can be utilized and how much oxygen demanding material can be added. We have assumed that this demand can be met half the time. In all biologically mediated processes there are periods of transition or adaption. As conditions change time is required for a community of wood decay or any other group of organisms to adapt to new conditions and become active. The manipulation of the soil environment with added oxygen demanding materials may lead to more frequent or rapid changes in conditions. This would most likely result in decreased rates of decay. Since there is no reasonable way to estimate the number of such days they are not included in the example.

This calculation was done to determine whether the extension in pole life was significant enough to warrant further work. Clearly, from this theoretical examination the potential exists to decrease the number of days when active decay would be occurring by over 50%. The amount of oxygen demanding material required is not unreasonable. The relationship between active rot days and pole lifetime is not at all clear, but if it is linear, significant extension of pole life is possible. We have conducted field and laboratory testing to determine whether the potential identified in these calculations can be achieved. The preliminary results of this testing program are presented below.

Table 2. Comparison of number of days/year when soil is not conducive to wood decay under natural and oxygen demand amended conditions.

Conditions in soil	Natural Conditions	Amended Conditions	Oxygen Demand ^a
No Rot days= too cold (80) + too dry (20)	100	100	0
Saturated Conditions (anaerobic days)	20	120	25
Partially Saturated (O ₂ Flux <5%)	50	100	1,800
Total Protected Days	170	320	

^a This calculation is based on maintaining anaerobiosis in an area 2.5 cm out from the surface of a 30 cm diameter (12") pole by adding a six carbon sugar. Units are in grams of carbon needed per year.

Experimental Methods

This study began on 4/14/95 with the collection of a creosote treated utility pole (believed to have been hit by an automobile) and a sample of rotting wood from another pole (both poles from Duke Power, Chapel Hill, NC). The piece of telephone pole was then cut into 0.5 in x 0.5 in. x 10 in. model test-poles. Model test poles were tested with various preservative treatments (no treatment, polyethylene wrap only, carbon source only, saturated salt solution only, 10% sodium dodecyl sulfate (SDS) solution only, carbon source + wrap, salt + wrap, and SDS and wrap). On 4/20/95, these test-poles were introduced into an aquarium containing approximately 7 kg of soil from the Schenk forest (Raleigh, NC) and an inoculum (100 g) of the brown rot wood (broken in to small pieces by hand). The aquarium was kept at room temperature in alternating cycles of dark and light and maintained at a high moisture content by repeated additions of deionized water. At approximately 2-3 week intervals the test poles were retreated with the amendments. On 9/25/95, test-poles (one no treatment and one carbon source only) were taken from the aquarium for breaking along with 3 test-poles which had never been exposed to the wood-rot organisms.

On 12/8/95, additional model poles were removed from the aquarium (no treatment, wrap only, carbon source only, salt wrap, and SDS wrap), dried and tested in the manner described below.

An additional set of test-poles were placed in an outdoor test bed in central North Carolina in a typical sandy-loam soil. They were subject to the same treatment regime imposed on the model poles in the aquaria, and tested in the same manner.

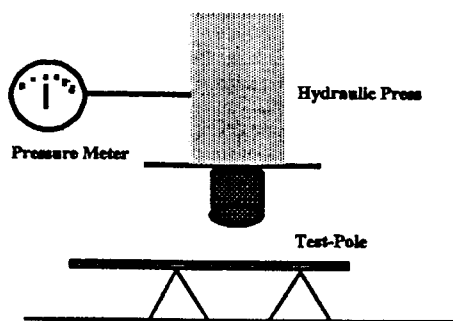


Figure 2. Schematic of pole breaking apparatus

Pole Testing

All test-poles were weighed, dried in a 55° C oven for 12 hours and reweighed. When constant weight was reached, the model poles were placed on the test apparatus, which was built as a scaled down version of the apparatus described by ASTM for the 'static bending' of small, clear, timber specimens (D143-52)(1). The bearing block (Fig. 2) was scaled down and the distance between the bearing plates was reduced to 4 inches. Because of this width, each 10 inch test-pole could be sampled twice, once at the ground line and once well above the ground line (the clean end of the test-pole). In each test, the maximum pressure exerted by the bearing block was recorded as the breaking pressure.

Results and Conclusions

Laboratory studies were conducted with model test poles in aquaria that had been seeded with wood rotting microorganisms found associated with a failed utility pole. We felt this would provide the most rapid degradation of the creosote treated test poles. The ASTM procedure for static bending strength was used to assess strength. In each case the same pole is "broken" twice, once on the end that had not been in the ground and again at the ground line level. In each case the strength change is calculated compared to the same model pole. Means are derived from data from multiple poles. The results shown in Figure 3 are preliminary data collected after 270 days exposure. It is clear that the changes observed are all within the range of variability in the breaking strength from pole to pole. This range is approximately 20%. Our observations suggest that the mean untreated pole had lost approximately 5% of its strength over this period, although some had lost as much as 20% of their strength. The poles treated with added carbon source had a mean value slightly stronger than untreated wood, with none showing any loss in strength. We currently have no explanation for why this treatment might increase the strength of the wood, although we can speculate that osmotic effects from the added carbon source might have a slight effect on strength. While not yet statistically significant this trend was consistent over multiple poles. Results with other treating materials (salt or detergent [SDS]) suggest no difference from the control poles through this stage of testing. Some test poles received a polyethylene wrap in addition to the chemical treatments. The objective was to see if this physical barrier provided additional advantages. To date we have seen no difference between the wrapped test poles and those treated with chemical amendments alone. This testing was conducted with almost new creosote treated wood and so it is not surprising that little degradation had occurred over the test period. This testing program is still in progress as are additional tests with poles treated with pentachlorophenol, CCA, and untreated wood.

We also conducted testing with the same type test poles placed in the ground in Chapel Hill, North

Carolina. The treatments were the same as those used in the laboratory studies, i.e. salt, carbon source, and SDS amendments, with and without polyethylene film wraps. Retreatment was approximately every 3-4 weeks. The results are shown in Figure 4. In this case the variability in the untreated poles was somewhat larger and the results are too preliminary to draw broad conclusions. The trends noted, however, are identical to those resulting from the laboratory tests. While the untreated poles showed between 10-15% loss in strength over the 270 day period, there was no loss in the treated poles, indeed a slight increase in resistance to breakage. Testing is continuing at this site and underway at others in the southeastern U.S.

The preliminary test data all suggest that the addition of readily degradable carbon sources seems to offer some protection potential for the wood. The critical step in turning this potential into a useful treatment process is a delivery system for the carbon amendment. This is the basis of the TRILAB⁴ process. Work is in progress on using the biodegradation potential of natural microbial communities to control the slow release of carbon sources embedded in a biodegradable plastic matrix⁵.

⁴Patent Pending

⁵Patent Pending

Figure 3. Effect of Carbon Amendment to Surrounding Soil on Test Pole Strength: Accelerated Studies

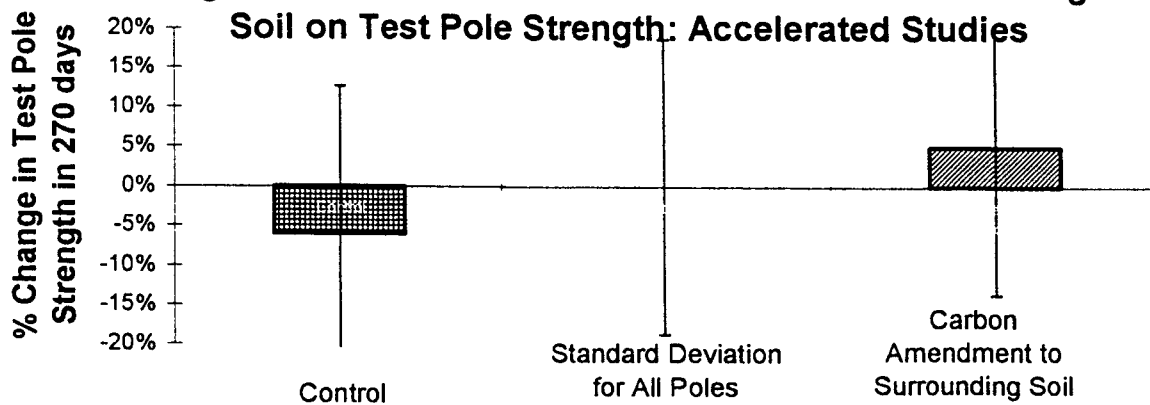
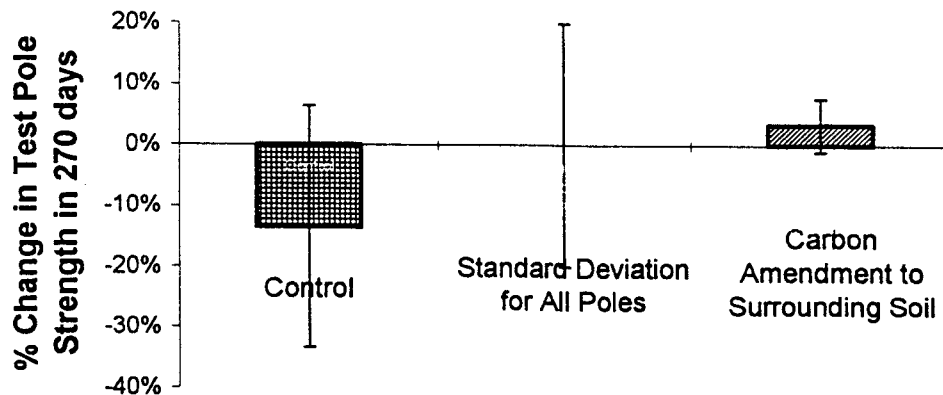


Figure 4. Effect of Carbon Amendment to Surrounding Soil on Test Pole Strength: Field Studies



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