Pipe Corrosion and Protective Coatings

Bob H. Welch,* Transportation Research Board

Fifty-eight pipe culvert installations were sampled for durability characteristics; the samples were assigned a relative pipe rating value for the purpose of numerical analyses and correlation with corrosive environmental soil and water conditions. The independent variables used included chemical composition of the water and soil, pH, total soluble salt content, minimum resistivity, resistivity at the naturally occurring soil moisture content, resistivity using the corresponding field water, and age of the pipe. Results indicate the total soluble salts is a more significant factor than any single soluble salt content in predicting the performance of pipe material. All soil sites examined eventually reached a soluble salt content of 0.8 percent. The corrosive effects of the solubles peak at approximately the 5 percent level. The effects of pH and minimum resistivity are found to be higher at the lower soluble salt content (<1.5 percent), and both lose their dominance at higher salt concentrations. Minimum resistivity, in particular, loses its effect on pipe life expectancies at a solubles content greater than 1.5 or 2 percent. The criterion used to predict pipe performance correlates very well with field observations and varies only in areas beyond the limits of the selection criteria.

Durability is one of the important factors that must be considered when a particular type of culvert pipe material is selected to be used in a given environment. Durability greatly influences the service life of a culvert; it is often the main criterion for choosing a particular material, as well as its thickness and the protective coating that it should have. Experience of many engineers and studies by various investigators have indicated that specific environmental characteristics of the culvert backfill soil and runoff waters greatly influence the corrosion performance of various pipe materials and coatings. There are some discrepancies about the environmental parameters that cause material corrosion and their relative quantitative effects.

The guidelines and recommended criteria for selecting culvert material are based on environmental conditions that are most prevalent in Utah soils, i.e., an average resistivity of approximately 11.0 Ω·m, an average pH of 8.3, and an average soluble salt content of 1.5 percent (alkaline soils principally with low sulfate contents). In addition, few drainage structures in Utah have continuous water runoffs; many are in semiarid climates where drainage flows are intermittent. Therefore, the findings and conclusions presented here should be extrapolated to other environmental limits with caution.

A random sampling of pipe materials for corrosion and abrasion analysis was chosen so that a variety of pipe materials and environmental surroundings and a wide span of time in place would be included. Pipes whose history of placement and specifications were not complete were eliminated from consideration. Six categories of pipe materials were evaluated: reinforced concrete, corrugated galvanized steel, aluminum alloy, bitumen-coated corrugated galvanized steel, bitumen-coated asbestos-bonded corrugated galvanized steel, and structural plate corrugated galvanized steel.

When the pipes were inspected, the following information was recorded on forms: type of pipe, height of backfill, degree of corrosion, type of corrosion, location of corrosion, visual observations, slope of pipe and channel, degree of erosive scour, topographic description, degree of abrasion, and any additional remarks about the condition of the pipe or its environmental surroundings. Then a 10-cm-diameter (4-in) core was drilled out of the pipe. For consistency among core samples, the samples were taken 3.6 m (12 ft) from the pipe end and 15 deg up from the pipe invert.

Soil samples were taken from the soil side of the culvert and placed in waterproof containers to be analyzed in the laboratory at a later date. Where runoff waters were discharging through the culvert, a corresponding water sample was also obtained. Pictures were taken of the surrounding topography, the invert, and the soil side of the pipe.

Soil samples were analyzed for the following: percentage of natural moisture, total soluble salts, soil pH, minimum resistivity, silicon dioxide, iron oxide, aluminum oxide, calcium oxide, magnesium oxide, soluble sodium oxide, insoluble sodium oxide, soluble potassium oxide, insoluble potassium oxide, chlorine, carbon dioxide, sulfates, and organics. Soil samples received

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*The author was with the Utah Department of Transportation when this paper was written.

from drainage structures having a runoff also were tested for minimum resistivity by using the field water instead of distilled water. Water samples, where available, were analyzed for sulfate, chlorine, calcium oxide, magnesium oxide, sodium oxide, potassium oxide, and carbon dioxide content in parts per million.

Core samples were first cleaned of any loose debris and then visually evaluated by three people and assigned a tentative pipe rating (PR) on a scale from 10 (excellent) to 0 (failure). These cores were then randomly measured in five locations for thickness to the nearest 0.0025 cm (0.001 in) and weighed. An average of the five thickness measurements was used as the thickness number. These samples were stripped of their zinc coatings and were again measured and weighed. The tentative pipe rating evaluations were reviewed based on visual observations of condition of the core metal of each sample. Final pipe ratings then were assigned each specimen after the field notes at each location, photographs of each location, and observations of the 10-cm (4-in) cores were compiled. This PR became the final number designating the relative degree of corrosion sustained by each pipe, which was used in numerical analysis.

The statistical and numerical analyses of data on the soil and water samples were categorized in three main areas. First a simple correlation coefficient matrix was determined by using all variables from all samples for possible correlation or dependency between environmental parameters. The pipe ratings, pipe ages in place, before and after core thicknesses, before and after core weights, design material weights and thicknesses, and combinations of their ratios were included in the data analysis. Then the results from this analysis were used to determine correlations between combinations of single independent parameters. Finally, multiple linear regression analysis was performed on both the single parameters and the groups of parameters.

Inasmuch as PR = 2 indicates that a pipe needs maintenance or replacement (not necessarily structural or hydraulic failure), PR = 2 was set as a constant in the equations, which were then solved for age. Inasmuch as the corrosion process may not be linear with respect to time, the age scale was adjusted so the equation adequately described the correlation of a PR = 2 and age to the condition of PR = 2. From these equations, the constant was adjusted for various types of coatings and metal thicknesses.

For each of implementation, these equations then were plotted for use by materials engineers as a guide in selecting pipe culvert materials.

Results presented are primarily geared toward the useful design life of underground culvert materials. These results may also be applicable to similar underground installations such as storm drains, cross drains, side drains, or bin walls exposed to underground, long-term deterioration by the immediate soil environment.

Inspection of culvert pipes throughout Utah indicated that the durability criteria of corrosion and abrasion should be given adequate consideration in the design and planning phases of highway development in conjunction with structural, hydraulic, construction, material availability, and economic factors.

At the test sites selected throughout Utah, there are no acidic soils (pH < 7). The pH of all soils is in the alkaline range. The only areas where acidic attack on underground pipe materials may be a problem are very isolated and unique instances. In these areas the runoff waters could possibly be acidic; however, the soil remains predominantly alkaline. Some general observations regarding pipe corrosion and durability based on investigations of several pipe sites are as follows:

1. Pipe extremities (the outer 1.8 to 2.4 m or 6 to 8 ft) corrode at a much faster rate than the interior of the pipe;
2. The exterior circumference of the pipe corrodes at approximately the same rate; and
3. Corrosion was a problem predominantly on the exterior or soil side of the pipe and not on the invert side.

In general, because of the predominantly flat topography and basically arid or semiarid climates that characterize the sites examined and because only six of the locations had a continuous year-round water flow, abrasion and scouring did not seem to be a problem for most pipe installations. Sediment buildup was a more serious problem than scour or invert abrasion in the majority of instances.

Specific results of the statistical analysis of the data obtained from the soil and water around each pipe location include a simple correlation matrix for each class of pipe and all pipe classes together. Table 1 gives the simple correlation coefficients for each class of pipe. Aside from the more widely accepted independent variables of age and soil pH, the following variables are used:

Variable	Symbol
Independent	
Minimum soil resistivity	R
Total soluble salts	SS
Natural moisture content	NM
Dependent	
Pipe rating	PR
Metal loss	ML
Highest pipe rating	HPR
Lowest pipe rating	LPR
Highest pipe rating - lowest pipe rating	HPR-LPR

The results of this analysis indicate that no single or group of single parameters of age, SS, or pH adequately explains the deterioration process of underground drainage structures. From the table, the single most important parameter, if used by itself to describe pipe performances, is the minimum soil resistivity.

Figure 1 shows pipe ratings versus resistivity. Although resistivity may be the single most important variable, based on the widely scattered data in Figure 1 and field experience, it alone is not reliable enough to explain pipe corrosion.

To expand the simple correlation matrices to include combinations of SS, pH, R, and age together with analysis of chemical components of the water and soil seems necessary to better explain the corrosion phenomenon. Several combinations of these variables were analyzed; those used are summarized by Welch (1).

Because no single soil parameter or groups of independent soil parameters adequately explain or can be used to predict pipe performance, a multiple linear regression analysis was performed. Two equations, each significant at the 0.05 level and containing the environmental parameters that can easily be evaluated for future pipe locations, were selected as the most suitable to represent the interaction of these environmental parameters and pipe performance. The formula for concrete is

$$\text{Log PR} = 0.66 + 0.18 \log [R/(SS \times pH \times age)] \tag{1}$$

and that for plain corrugated steel pipe is

$$PR = 9.25 + 0.15SS + 0.007 [R/(SS \times pH)] - (0.0013 \times SS \times pH \times age) - 0.06pH^2 \tag{2}$$

A pipe rating of two is considered a pipe failure from the durability or corrosion viewpoint. Only two pipes sampled actually had this rating. PR = 2 does not constitute a structural failure but rather an impending failure for which maintenance or replacement should be initiated. The pipes may not necessarily corrode at a uniform rate once corrosive attack has begun or when the pipe material nears the failure point, as shown in Figure 2. The rate of corrosion $\partial PR/\partial t$ for a particular pipe material at a given location is a function of the pipe's surrounding soil and water conditions. This report does not document the increasing rates of corrosion

Figure 1. Minimum soil resistivity.

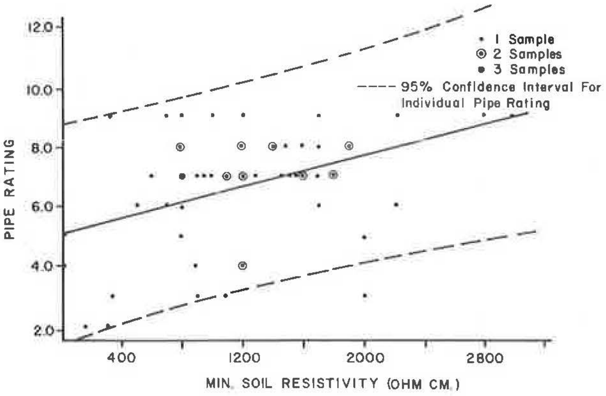

Figure 2. Time adjustment for multiple linear correlation analysis.

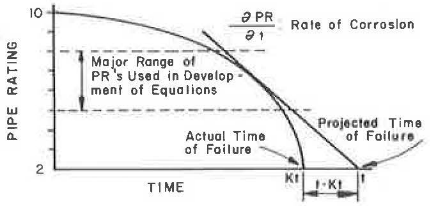

Figure 3. Material selection criteria.

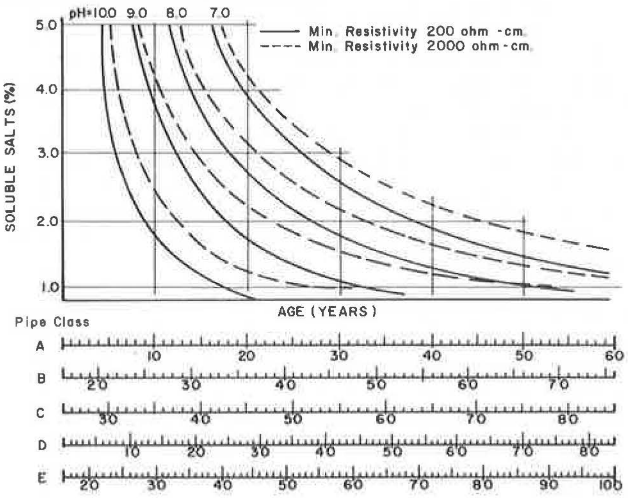

Figure 4. Concrete material selection criteria.

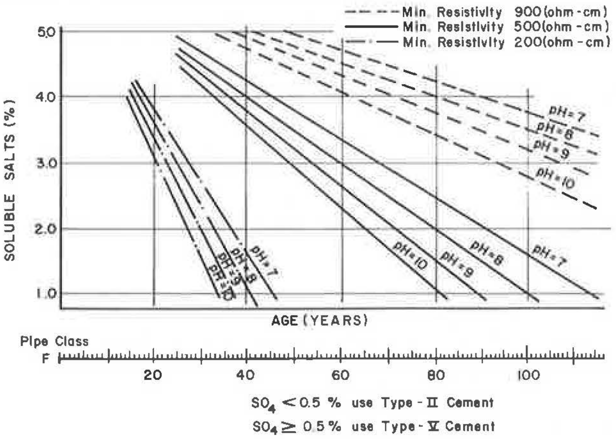

Table 1. Simple correlation coefficients of various pipe materials.

Pipe	Variable	PR	HPR	LPR	HPR-LPR	ML	Age	SS	pH	R	NM
Concrete	PR	1.000	0.712	0.934	-0.401		-0.231	-0.493	0.188	0.684	
	HPR		1.000	0.436	0.349		0.321	-0.169	0.245	0.501	
	LPR			1.000	-0.691		-0.173	0.613	0.104	0.584	
	HPR-LPR				1.000		-0.078	0.503	0.089	-0.134	
	Age						1.000	0.441	0.121	-0.357	
	SS							1.000	0.342	-0.353	
	pH								1.000	0.142	
	R									1.000	
Asbestos-bonded, bitumen-coated corrugated steel	PR	1.000				-0.245	0.008	0.632	0.632	0.605	-0.409
	ML					1.000	0.557	-0.577	0.265	-0.366	0.058
	Age						1.000	-0.616	0.077	0.164	0.394
	SS							1.000	-0.213	0.229	-0.253
	pH								1.000	-0.489	0.141
	R									1.000	0.031
	NM										1.000
Bitumen-coated corrugated steel	PR	1.000				-0.742	-0.140	-0.485	0.235	-0.095	0.669
	ML					1.000	0.482	0.946	-0.472	-0.541	-0.011
	Age						1.000	0.577	0.420	-0.180	0.176
	SS							1.000	-0.485	-0.744	0.305
	pH								1.000	0.725	-0.311
	R									1.000	-0.792
	NM										1.000
Plain corrugated steel	PR	1.000					-0.126	0.039	-0.308	0.428	
	Age						1.000	-0.191	0.102	-0.194	
	SS							1.000	-0.260	-0.221	
	pH								1.000	-0.004	
	R									1.000	
All samples	PR	1.000					-0.206	-0.084	-0.212	0.444	-0.313
	Age						1.000	-0.164	0.096	-0.287	0.107
	SS							1.000	-0.248	-0.217	0.046
	pH								1.000	0.081	-0.095
	R									1.000	-0.190
	NM										1.000

with respect to time; the approach is presented here because it does provide a rational explanation of equations 1 and 2 with respect to service history. Because the equation developed by the multiple linear regression method and the majority of data fall between pipe ratings of 4.5 and 8 and because actual pipe deterioration is not linear with respect to time, the projected failure time is some time factor (t - Kt) greater than the actual failure time projected by the equations. Based on the observations of pipes in service, the K constant is 0.01 for equation 1 and 0.15 for equation 2.

Using this criterion to compare service life with pipe rating in two situations, the data collected in this study and results of 40 independent pipe tests have shown these selection procedures to be accurate to ±3 years at 0.05 significance level. Figure 3 shows equation 2 plotted against the following pipe scales:

Symbol	Pipe
A	Corrugated galvanized steel
B	Bitumen-coated corrugated galvanized steel, aluminum alloy, corrugated steel coated with pitch resin adhesive
C	Asbestos-bonded bitumen-coated corrugated steel
D	Plain corrugated steel structural plate
E	Bitumen-coated corrugated steel structural plate, aluminum alloy structural plate
F	Types 2 and 5 portland cement concrete

Figure 4 shows equation 1 plotted for type 2 portland cement concrete pipe. It should be noted that Figure 4 for concrete pipe is found to work in Utah's alkaline soils except at three locations. The soil at these locations had a sulfate content of 0.5 percent or higher. Therefore, in soils containing more than 0.5 percent sulfate, a type 5 cement is recommended.

From Figure 3, for pipe class D, the effects of resistivity and pH on service life are much greater at a lower soluble salt range (<2 percent) than at higher soluble salt ranges. More than 2 percent soluble salts indicate that resistivity becomes a secondary factor affecting durability, and the effects of pH are slightly reduced. The scale for soil solubles runs from 0.8 percent to 5.0 percent because the relative effects of a total soluble salt content above 5 percent are not appreciably greater than at the 5 percent level. A minimum level of 0.8 percent is recommended because (a) soluble salts below 0.8 percent are not the primary contributing factors to corrosion (pH and resistivity are) and (b) the older pipe locations inspected have accumulated higher salt content levels than may have originally existed at these locations because of applications of deicing salt, for example (2).

Our test data and other data accumulated from soil testing throughout Utah were compared to the iso maps presented by Meshgin (3) for possible use in lieu of a complete soil analysis at each pipe location. These data also were compared to the very detailed surface iso maps provided by the U.S. Department of Agriculture (4). Soil characteristics, particularly soluble salts, pH, and minimum resistivity, vary too much from one location to another to use the iso maps effectively without a large error in proper pipe material selection. Therefore, in the preconstruction phase of highway design, the materials engineer should sample soils in pipe culvert locations to identify potentially agressive areas. However, the iso maps could be helpful in providing an indication of the soil conditions in the corresponding drainage basin.

To apply the field data on deterioration of pipes made of various materials to new culvert materials and coatings requires a relatively rapid laboratory method for evaluating potential durability or resistance to corrosion. The results of the salt chamber, ozone, and electrolytic cell test determinations (1) indicate that these methods are not suitable for rapid evaluation of durability and corrosion resistance.

The mudpack test (1) after 8 weeks' exposure did cause noticeable deterioration of some pipe samples. Flakes of the galvanized steel coating and some local pitting occurred on the plain corrugated steel pipes and the plain corrugated structural steel plate pipes. The aluminum alloy cladding turned dark after 7 days' exposure and formed a uniform rough oxide coating after 3 weeks' exposure. This condition of the aluminum alloy remained unchanged throughout the entire 8-week exposure period. On all of the uncoated steel pipes, a salt-like crystalline structure built up around the samples on top of the mudpack. The corrugated steel pipe coated with pitch-resin adhesive had some adhesion loss along the edges but showed no signs of change on the coated side; however, the invert side did lose approximately 5 percent of the coating, and the remaining material had lost a considerable amount of its adhesive properties.

The bitumen-coated corrugated steel pipe sample showed no corrosion beneath the bituminous coating where it was totally intact after the mudpack test. Near the edges where the core metal had been exposed, the bituminous coating lost adhesion to the metal. The bituminous coating also had a tendency to flow at a temperature of 38° C (100° F) after the 8-week period. The asbestos-bonded bituminous coatings remained in good condition throughout the test and showed only slight adhesion loss near the edges where the base metal had been exposed.

Metal structures subjected to potential aggressive attack from alkaline soils can be identified if minimum resistivity, pH, and total soluble salts are known. By analyzing their combined effects, acceptable predictions can be made about the resistance of the steel to corrosion. At lower soluble salt contents, the rate of corrosion is highly dependent on the minimum resistivity and pH whereas high salt contents will in themselves be the principal corrosion-causing agent.

Deterioration of concrete pipes also is highly dependent on pH, soluble salts, and minimum resistivity in alkaline soil environments. However, the sulfate content in amounts of more than 0.5 percent may be the principal deterioration agent.

A more extensive laboratory mudpack testing program to quantify the relative effects of temperature, resistivity, pH, type of water, duration of test, sulfates, wetting-drying, and total soluble salts on various pipe materials should be undertaken. Included with these parameters, an electrolytic cell test should be applied to the various materials for optimum results. Based on the results of this investigation, the mudpack test is recommended for quantifying in a relatively short period of time the comparative durability characteristics of various pipe culvert materials. In conjunction with this recommendation, a universal method of pipe evaluation of culvert materials should be developed so information concerning corrosion or abrasion may be more fully used by design and materials engineers in areas where the information has not been accumulated. Only with this type of liaison can the optimum use and exchange of data describing laboratory and field durability be implemented and a single set of reliable corrosion standards be adopted by all highway agencies.

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