because of friction and the presence of some natural bond between the components of the member.

However, a member may be considered to have full composite action if one of the components of the member fails without rupturing the shear connection. This type of failure was achieved in two of the three composite specimens. The third composite specimen did show a horizontal shear failure but only after the load equaled the failure load of the other composite specimens.

INTERPRETATION OF RESULTS

The expected mode of failure in flexural members without adhesive bonding is a horizontal shear failure at the interface between the two dissimilar materials. All of the noncomposite specimens did fail in horizontal shear between the concrete slab and the metal deck. The dimensions of the slab unit were selected so that each specimen could resist a uniform loading of 5 kPa (100 lbf/ft^2). No natural bond between the concrete and metal deck was assumed for these calculations. However, the unbonded members all carried load well in excess of their computed capacity, which indicated the presence of a relatively high percentage of partial composite action.

In this program, failure was considered as a lack of serviceability of the unit. In the case of the noncomposite control specimens, this lack of serviceability was defined by horizontal shear and separation of the decking from the slab. In two of the three composite specimens, no horizontal shear failure occurred and lack of serviceability was defined by excessive deflection. The load-deflection curves (see Figure 4) show that the adhesive-bonded composite specimens deflected less than the noncomposite control specimens by an average of 15 percent.

CONCLUSIONS AND RECOMMENDATIONS

As defined by serviceability criteria, the composite specimens carried more than twice the load of their unbonded counterparts. These results demonstrate that the adhesive-bonded concrete-metal deck member can achieve full composite action (3,6).

It is difficult to form a comparison based on ultimate load because two of the three composite specimens never actually reached an ultimate load but continued to deflect with increasing load. These tests were terminated because the deflection exceeded the stroke of the testing machine. The one composite specimen that demonstrated horizontal shear failure showed only an 8 percent increase in ultimate load capacity compared with its unbonded counterparts.

Some aspects of adhesive bonding that might be recommended for study include the following:

1. Long-term creep effects on the effectiveness of the adhesive shear connection,
2. Determination of the amount of natural bond that exists between the slab and the metal deck,
3. The effects of cyclic and impact loading on the adhesive shear connection, and
4. Definition of the amount of permissible slip between the slab and the metal deck, which should be correlated with a study of the properties of various adhesives.

The results presented here are not expected to have any immediate impact on current practice, but they are one more contribution to the growing history of adhesive-bonded composite members.

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Evaluation of the Durability of Metal Drainage Pipe

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Preliminary results are presented of a 10-year field study undertaken in Louisiana to determine the ability of aluminum and galvanized-steel culverts to resist corrosion in moderate, acidic, and low-electrical-resistivity environments. In 1973, 10 types of aluminum and galvanized-steel culverts were installed, generally as side drains, at 10 test locations. One pair of each type of culvert was installed at each site. Every two years, investigators are removing one designated culvert of each of the pairs and subjectively rating the condition of the metal and protective coating. Field samples of the culverts are evaluated in the laboratory, and the test culverts are installed again after each inspection. The undisturbed mate of each pair remains buried for the duration of the study to analyze the impact of the periodic inspections. After 6 years of field exposure, the asbestos-bonded, bituminous-coated, galvanized-steel culvert is resisting corrosion quite well even in brackish water, an environment characterized by low electrical resistivity. Several aluminum and coated galvanized-steel culverts appear to be well suited for the normal range of acidic environments encountered in Louisiana. All of the test culverts appear to provide satisfactory service life in the test environment designated as moderate.

Figure 1. Location of test sites.

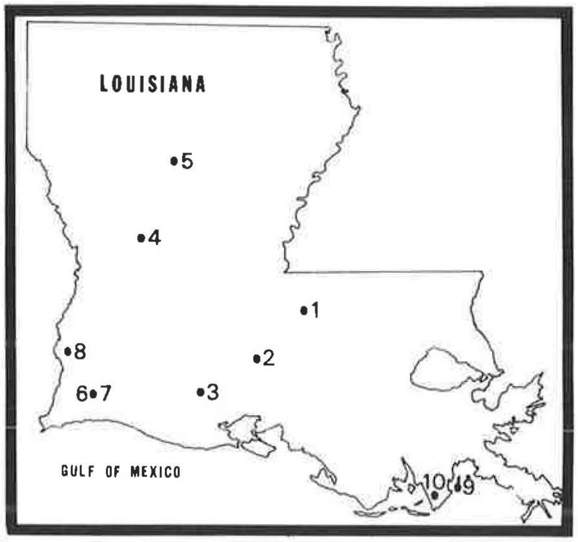


Table 1. Soil and effluent characteristics at test sites.

	Soil			Effluent	
Site	Type	Electrical Resistivity (Ω/cm³)	pH	Electrical Resistivity (Ω/cm³)	pH
1	Clay	1 038	6.4	11 750	6.4
2	Silty clay	812	7.5	4 280	7.3
3	Silty clay	1 268	6.9	5 460	7.0
4	Silty sand	11 323	5.3	20 667	5.6
5	Sand	3 479	6.6	2 333	6.6
6	Sandy clay	314	8.2	135	7.0
7	Sandy silt	456	8.1	133	7.1
8	Silty clay	3 437	5.5	16 200	6.8
9	Sand	971	8.4	338	7.7
10	Silty clay	254	8.2	121	7.3

The wetlands state of Louisiana receives approximately 152 cm (60 in) of rainfall each year. Road design engineers of the Louisiana Department of Transportation and Development (LADOTD) must assign cross slopes and texture to highways to rid them of this water. Hydraulics design engineers must then apply appurtenances such as drainage pipes to remove the water from highway rights-of-way. LADOTD hydraulics engineers can generally choose either reinforced concrete or corrugated metal pipe in their designs. Concrete pipe is very durable (1) and, under stable bedding conditions, can normally serve effectively for the life of a highway.

LADOTD recognizes that metal pipe has its place in the field of hydraulics and maintains an interest in innovations in metal pipe. Metal pipe is relatively lightweight, an advantage that gains significance as the size of the pipe increases. Because metal pipe is also relatively flexible, it deflects rather than breaking under heavy loads or when underlying support is lost. The major drawback of metal pipe is its tendency to corrode in the presence of moisture, oxygen, and salt. Additional information is needed on the rates at which aluminum or galvanized-steel pipe corrodes in the variety of environments found in Louisiana.

The Federal Highway Administration (FHWA) has identified the pH and electrical resistivity of the environment as major factors in metal culvert corrosion (2). This concept is particularly applicable in Louisiana. Previous research by LADOTD has related corrosion rates for metal culvert with general geological soil areas, which in turn have been associated with pH and electrical resistivity levels (1).

Metal culvert corrosion in Louisiana can be analyzed in terms of three general environments. The geographic heart of the state can be termed a moderate environment. The pH values of soil and effluent in this area typically range from 6 to 8, and electrical resistivity values are usually greater than 2000 Ω/cm³. In the Gulf of Mexico region, pH values range from 6 to 9 and electrical resistivity values are less than 2000 Ω/cm³ because of the inland intrusion of salt water. The hills of northwest and west-central Louisiana plus a portion of the eastern flatwoods represent a third type of environment in which electrical resistivity values exceed 2000 Ω/cm³ but pH values approach 5 on the acid side of the hydrogen ion scale.

In 1972, the state found itself with a continuing need for drainage, a diverse set of environments, and a wide array of remedies offered by the metal culvert industry. The state responded with a major 10-year field study to determine the ability of available aluminum and galvanized-steel culverts to resist corrosion in moderate, acidic, and low-electrical-resistivity environments. A limited laboratory study parallels the field evaluations.

METHOD OF PROCEDURE

Site Selection

Research engineers initially selected 10 locations, spread across the state, as test sites (see Figure 1). These sites represented the spectrum of moderate, acidic, and low-electrical-resistivity (R) environments, as follows:

	Minimum Soil Resistivity	
Soil pH	<2000 Ω/cm³	>2000 Ω/cm³
5.0-6.0		Sites 4 and 8 (acidic)
6.1-7.0	Sites 1 and 3 (low R)	Site 5 (moderate)
7.1-8.0	Site 2 (low R)	
8.1-9.0	Sites 6, 7, 9, and 10 (low R)	

Table 1 gives the characteristics of the soil and effluent at the test sites. Sites 6 and 7 are ditch and canal installations, respectively, and are located on opposing sides of the highway at that location.

Materials Tested

Eleven varieties of coated and uncoated aluminum and galvanized-steel culverts were selected for evaluation. The corrugated test culverts were 1.2 m (4 ft) long and 46 cm (18 in) in diameter, except for the aluminum plate arch, which was approximately 1.4 m (4.5 ft) square.

The following types of culverts are commonly known:

1. Uncoated, 0.15-cm (16-gauge) galvanized-steel pipe (AASHTO M36);
2. A 0.15-cm galvanized-steel pipe, coated with asphalt of typical thicknesses of 0.14 cm (55 mils) on the interior and 0.12 cm (48 mils) on the xterior of the pipe (AASHTO M190);
3. A 0.19-cm (14-gauge) galvanized-steel pipe,

coated with asbestos-bonded asphalt of typical thicknesses of 0.14 cm (55 mils) on the interior and 0.16 cm (64 mils) on the exterior (LADOTD 1977 Standard Specifications for Roads and Bridges);

4. Uncoated, 0.15-cm clad aluminum alloy pipe (AASHTO M196);

5. A 0.15-cm clad aluminum alloy pipe, coated with asphalt of typical thickness of 0.13 cm (50 mils) on the interior and on the exterior (AASHTO M190, type A); and

6. A 0.27-cm (12-gauge) aluminum alloy structural plate arch (AASHTO M196).

The following five types of test culverts are new products:

1. A 0.15-cm galvanized-steel pipe with a 0.03-cm (12-mil), coal-tar-based laminate applied to the interior and a 0.008-mm (0.3-mil) modified-epoxy coating on the exterior (AASHTO M246);

2. A 0.15-cm galvanized-steel pipe with a 0.05-cm (20-mil), coal-tar-based laminate applied to the interior and a 0.008-mm (0.3-mil) modified-epoxy coating on the exterior (AASHTO M246);

3. A 0.15-cm galvanized-steel pipe with a 0.02-cm (10-mil) interior and 0.08-mm (3-mil) exterior polyethylene coating (AASHTO M246);

4. A 0.15-cm galvanized-steel pipe with a 0.03-cm (12-mil) interior and 0.01-cm (5-mil) exterior polyethylene coating (AASHTO M246); and

5. A 0.15-cm galvanized-steel pipe with a 0.02-cm (10-mil) interior and 0.08-mm (3-mil) exterior plasticized-vinyl-resin coating (AASHTO M246).

Field Installation

In 1973, LADOTD research and maintenance personnel installed 20 sections of culvert at each of the 10 selected locations. Two sections of each type of culvert were buried in all locations, one section to be removed periodically for evaluation and reinstallation and the other to remain undisturbed for the duration of the 10-year study.

A "Grade-All" was used to remove all grass and debris from the ditches at the test sites for approximately 61 m (200 ft) to facilitate the installation. Next, the top 0.6 m (2 ft) of in-place soil was removed, and the pipes were lowered into the ditch by hand and spaced approximately 1.8 m (6 ft) apart. The removed soil was then used to cover the individual pipe sections to provide a minimum cover of 0.3 m (1 ft). A similar installation procedure was used at the two water sites, where the drainage pipes were installed along the side of drainage canals parallel to state highways that run through the coastal marshes. The pipe sections were installed perpendicular to the roadway, half covered with soil and half extending out into the brackish water.

In 1975, research and maintenance personnel used the installation procedures described above to install one pair of an eleventh type of test pipe at each of the 10 sites. This was the galvanized-steel culvert with a plasticized-vinyl-resin polymer coating.

Field Inspection

In 1975, 1977, and 1979, a panel of research engineers and technicians inspected the culverts after two, four, and six years of field exposure, respectively. Maintenance personnel removed one designated pipe of each type at each site. The 1.2-m (4-ft) sections were then washed clean to remove as much of the soil as possible without removing the coatings. After the pipes were cleaned, photographs were taken from several angles to document their condition. Then the inspection panel, which consisted of two highway research engineers and three highway research engineering technicians, visually rated the pipes and coatings by using an evaluation report form.

The rate of corrosion is being studied in terms of the following criteria:

Rating	Category	Condition Under Visual Observation
0-1.0	Excellent	No signs of deterioration
1.1-2.0	Good	Very slight signs of deterioration and pitting
2.1-3.0	Fair	Moderate signs of deterioration and pitting
3.1-4.0	Poor	Extreme signs of deterioration and pitting
4.1-5.0	Very poor	Signs of complete deterioration; pipe no longer useful as a drainage tool

Coatings were also rated on a scale from zero to five, and notes were made of blisters, delamination, and removal from the metal.

The pipes were then sampled for laboratory examination. The sampling consisted of cutting an 8-cm (3-in) band off the end of each section removed. To provide protection between evaluations, an asphalt film was brushed on the metal edges that were exposed during the cutting process. When the field evaluation was completed, the pipes were returned to the ditch, oriented in their original positions, and covered with in-place soil.

Laboratory Analyses of Soil, Water, and Unexposed Culverts

Soil and water samples were initially collected from each installation site on a semiannual basis. Since the results from the semiannual samples showed relatively little change in pH and resistivity, the investigators have changed to sampling annually. These samples have been tested for pH and minimum resistivity in accordance with LADOTD laboratory procedures, which require the use of a pH meter and a resistivity meter as the basis of measurement. The soil samples were identified by field classification techniques.

The culvert testing program initially dealt with determination of the physical characteristics of the various metals and their protective coatings as manufactured. The amount of zinc coating was determined by weight loss as the coating was dissolved in an acid solution (ASTM A90). The thicknesses of the bituminous, asbestos, and various organic coatings were measured with a micrometer. The composition of steel and aluminum used in the culverts was determined by X-ray fluorescence, a process that provides a quantitative analysis of each element present in the metal alloys. Thickness and composition data are given elsewhere (3).

The durability of the culvert materials as manufactured has been evaluated in the laboratory by the use of three methods: salt-fog exposure, Weather-Ometer exposure, and accelerated corrosion by induced voltage.

Salt-fog exposure (ASTM B117) and Weather-Ometer exposure (ASTM D609) are described in LADOTD procedure TR1011-74. In the salt-fog test, culvert samples are subjected to a fog with 18 percent salt concentration, at approximately 57°C (135°F), for four weeks. In the Weather-Ometer test, culvert samples are subjected to ultraviolet light; an intermittent, pressure-controlled water spray; a temperature of approximately 63°C (145°F); and relative humidity of approximately 85 percent. Evaluations of the salt-fog and Weather-Ometer exposures are subjective and take the form of satisfactory or unsatisfactory ratings for the number of hours exposed. Initial test results are reported in the appendix of the report by Kinchen and others (3).

In the method of accelerated corrosion by induced voltage, technicians cut metal culvert samples that measure approximately 7.6x15.2 cm (3x6 in) and coat the exposed edges with epoxy. The samples are individually suspended in a series of wooden boxes that contain 0.1 percent salt solution. A galvanic cell is created by means of wires that interconnect the samples. An electrical potential difference of 12 V is induced across each sample by means of a battery charger. The samples are removed from the galvanic cell as signs of severe corrosion appear. The culverts are examined by X-ray to detect the presence of perforations in the metal. Radiographic analysis thus allows the samples to be checked for perforation without removal of the asphaltic or polymeric coatings. The results from this induced-voltage testing are not yet available.

It is hoped that a minimum relative life can be determined from these three laboratory test methods and, ultimately, that culvert life in the laboratory and in the field can be correlated.

RESULTS

General Evaluation

The basis of field performance is the ability of the culverts to withstand metallic corrosion. The culvert that provides the best performance after six years of field exposure is the asbestos-bonded, asphalt-coated, galvanized-steel pipe.

Panel ratings of the test culverts after two, four, and six years of field exposure are given in Table 2. Minor inconsistencies in time-successive ratings for a given culvert reflect the independence of the evaluations. Subsequent discussion will consider the performance of the test culverts in the three types of environments given in Table 2.

The aluminum-alloy and galvanized-steel culverts are experiencing the fastest corrosion rates at locations where the effluent and/or the soil exhibits low electrical resistivity. There are conditions of low electrical resistivity at four sites near the Gulf of Mexico (sites 6, 7, 9, and 10), where resistivity values for the effluent are 350 Ω/cm^3 or less, which is truly corrosive.

Low pH values are having less dramatic but still notable corrosive effects on the galvanized-steel culverts and no significant effects on the aluminum-alloy culverts. The pH values (5.3-5.5) referred to are low for Louisiana, where such values are normally above 5.5. The test environment designated as moderate is inducing corrosion at the slowest rate for the culverts as a group. Resistivity values of soil and effluent are greater than 2000 Ω/cm^3, and pH values center around 6.6 at this site.

Evaluation of Culverts by Type

Galvanized-Steel Culvert

Table 2 and Figures 2-4 reflect the rates of corrosion of the galvanized-steel test culverts and the relative corrosive nature of the three types of environments under consideration. As Table 2 indicates, corrosion of this type of test culvert was well under way after two years at a number of sites that are characterized by low electrical resistivity. An increase in the rate of corrosion can also be noted in Table 2 as the character of the environment changes from moderate to acidic and then to low electrical resistivity. Figure 2 shows the advanced level of corrosion in the galvanized-steel test culvert after six years in the low-resistivity (brackish-water) environment. Figure 3, a photograph taken after six years, shows that corrosion of this type of culvert is progressing at a slow but steady pace in an acidic environment. The soil-side corrosion shown in Figure 3 indicates that the nature of the soil as well as the nature of the effluent should be considered in specifying and designing metal culvert for durability. In Figure 4, the galvanized-steel test culvert is shown to be resisting corrosion quite well after six years in a moderate environment.

Coal-Tar-Based, Polymer-Coated, Galvanized-Steel Culvert

The panel's two-, four-, and six-year evaluation ratings of the coal-tar-based, polymer-coated, galvanized-steel test culverts are given in Table 2. Six-year ratings of the coatings per test site and per environment are given in Table 3.

Comparison of six-year panel ratings in Table 2 for the galvanized-steel test culverts with and without this particular polymeric coating reveals that the coating is providing a small to moderate measure of corrosion protection for the culverts in the acidic and low-resistivity environments. The data given in Table 2 also show that the resistance to corrosion offered by these polymer-coated culverts decreases significantly as electrical resistivity decreases. The panel assigned ratings of good at six years to the polymer-coated culverts at sites 1, 2, and 3 where soil resistivity is at the 1000-Ω/cm^3 level. However, the panel noted greater deterioration of these culverts at sites 6, 7, 9, and 10, where effluent resistivity is 350 Ω/cm^3 and less and thus gave these culverts ratings of fair to very poor. Minor corrosion of the rivets was noted at the acidic sites.

The panel noted that the 0.51-mm (20-mil) thick coal-tar-based polymer coating tends to separate from the metal in all of the various types of environments (Table 3). The 0.31-mm (12-mil) thick coating tends to so separate in an environment that exhibits extremely low resistivity. Polymeric coatings of both thicknesses were susceptible to the formation of pockets of air and moisture (i.e., blisters) in the low-resistivity environments.

Polyethylene-Coated, Galvanized-Steel Culvert

Comparison of panel ratings of galvanized-steel test culverts with and without the polyethylene coating (Table 2) indicates that this coating has generally provided substantial protection to the metal in the various test environments. The panel did note perforation of this type of culvert at site 6 after four years and at site 7 after six years. The effluent at these two sites is brackish. In addition, minor corrosion of the rivets and seams was common in the acidic and low-resistivity environments.

The outlook for continued protection is not so promising. This polymeric coating is blistering in all of the various types of test environments and separating from the metal in the moderate and low-resistivity environments (Table 3).

Table 2. Panel ratings of test culverts at two, four, and six years.

Type of Culvert	Years Exposed	Moderate Environment, Site 5	Acidic Environment, Site 4	Acidic Environment, Site 8	Low-Electrical-Resistivity Environment, Site 1	Site 2	Site 3	Site 6	Site 7	Site 9	Site 10
Uncoated galvanized steel	2	1.3	1.9	1.7	1.4	1.2	1.2	2.9	3.7	1.5	2.9
	4	2.0	2.0	2.4	1.4	1.2	2.2	2.8	5.0[a]	4.0[a]	5.0[a]
	6	1.8	2.4	2.2	2.2	2.0	3.0	4.4	5.0	4.5	5.0
	6			2.3				3.7			
Asphalt-coated galvanized steel	2	1.2	1.2	1.2	1.8	1.4	1.2	1.4	2.1	1.3	2.0
	4	1.6	1.2	1.8	1.4	1.8	1.8	2.2	4.4[a]	2.0	3.2[a]
	6	1.4	1.4	1.6	1.8	2.0	2.0	2.0	4.6	3.2	4.5
	6			1.5				2.9			
Asbestos-bonded asphalt-coated galvanized steel	2	1.2	1.2	1.2	1.8	1.2	1.2	1.2	1.4	1.3	1.5
	4	1.2	1.0	1.2	2.0	1.6	1.2	1.2	1.4	1.2	1.5
	6	1.0	1.0	1.4	2.2	2.0	1.8	1.2	1.4	2.0	2.0
	6			1.2				1.8			
Clad aluminum alloy (round)	2	1.6	1.5	1.4	1.2	1.8	1.3	3.2	3.2	2.7	3.1
	4	2.0	1.4	2.0	1.0	1.8	1.6	2.2	2.6	3.0	2.5
	6	2.0	1.6	1.8	1.4	2.0	2.4	4.2[a]	2.4	2.8	2.5
	6			1.7				2.5			
Asphalt-coated clad aluminum alloy (round)	2	1.2	1.2	1.2	1.8	1.4	1.2	1.4	2.1	1.3	2.0
	4	1.6	1.2	1.8	1.4	1.8	1.8	2.2	4.4	2.0	3.2
	6	1.6	1.4	2.0	1.6	2.0	2.0	2.6	2.0	2.5	2.5
	6			1.7				2.2			
Aluminum alloy structural plate	2	1.4	1.3	1.5	1.5	1.4	1.2	3.3	3.0	2.7	2.6
	4	1.8	1.0	1.8	1.0	1.2	1.2	2.8	2.8[a]	3.2	3.2
	6	2.2	2.0	1.8	2.0	2.0	2.0	2.6	2.6	3.8	3.5[a]
	6			1.9				2.9			
12-mil, coal-tar-based, polymer-coated galvanized steel	2	1.2	1.2	1.2	2.0	1.2	1.2	2.0	2.6	1.2	3.1
	4	1.8	2.0	2.2	1.0	1.4	1.4	2.6	4.0[a]	2.5	3.5
	6	1.8	2.0	2.0	1.6	2.0	2.0	3.2	4.0	4.0	4.5[a]
	6			2.0				3.0			
20-mil, coal-tar-based, polymer-coated galvanized steel	2	1.2	1.2	1.2	1.7	1.2	1.2	1.8	2.6	1.2	3.1
	4	1.8	1.6	2.0	1.2	2.0	1.8	2.4	4.0	2.5	3.5
	6	1.8	2.0	2.0	1.8	2.0	2.0	3.2	4.0	4.0	4.5[a]
	6			2.0				3.1			
Polyethylene-coated galvanized steel, 10-mil interior, 3-mil exterior	2	1.0	1.5	1.2	1.3	1.2	1.0	1.5	1.4	1.7	1.5
	4	1.8	2.0	1.8	1.8	2.0	1.6	2.2	2.4	3.0	2.2
	6	1.2	2.0	1.8	1.8	2.2	2.0	2.4	3.2[a]	2.2	–[b]
	6			1.9				2.3			
Polyethylene-coated galvanized steel, 12-mil interior, 5-mil exterior	2	1.0	1.4	1.2	1.2	1.0	1.0	1.5	1.4	1.7	1.5
	4	2.0	2.0	1.4	2.0	1.8	1.8	4.4[a]	2.2	2.2	2.0
	6	1.0	2.0	1.6	1.8	2.0	2.0	4.0	2.4	2.8	–[b]
	6			1.8				2.5			
Vinyl-coated galvanized steel, 10-mil interior, 3-mil exterior	2	1.0	1.0	1.0	1.0	1.0	1.0	2.2	1.8	2.0	2.0
	4	1.0	1.2	1.0	1.0	1.2	1.2	1.6	2.0	1.8	1.8
	4			1.1				1.5			

Note: 1 mil = 0.025 mm.
[a]Culvert perforation. [b]No rating available; test culvert missing.

Figure 2. Condition of galvanized-steel culvert in low-electrical-resistivity environment (site 10) after six years.

Figure 3. Condition of galvanized-steel culvert in acidic environment (site 4) after six years.

Vinyl-Coated, Galvanized-Steel Culvert

Two- and four-year panel ratings for the vinyl-coated, galvanized-steel culvert are given in Table 2, and the four-year ratings for this coating are given in Table 3. These culverts were installed two years after the other culverts under discussion here. The polymeric coating has thus far protected most of these culverts from significant corrosion. However, at the four brackish-water sites, the coating is blistering and separating from the metal culvert (Table 3). Additional time is required to properly evaluate the durability of this type of polymer-coated culvert, especially in moderate and acidic environments.

Asphalt-Coated, Galvanized-Steel Culvert

Comparison of ratings in Table 2 for the galvanized-steel culvert with and without the bituminous coating reveals that the coating is generally providing a moderate amount of corrosion protection. However, this protection is inadequate for the test environments with low resistivity, and at two brackish-water sites corrosion has rendered the culverts unfit as drainage tools.

The bituminous coatings being evaluated in this study are not adhering sufficiently to the steel culverts in any of the environments under consideration (Table 3). Research personnel noted a lack of adhesion in 1973 before the culverts were installed. The bituminous coating, softened under high summer temperatures, incurred minor scrapes during preinstallation transporting and handling. In subsequent years, the panel has also observed asphalt coating clinging to the soil after the culvert has been removed from the ditch line for inspection. For each bituminous-coated culvert so inspected, there is a mate that is being left undisturbed for the duration of the study. It will be interesting to observe the condition of these undisturbed pipes at the conclusion of the 10-year study.

Figure 4. Condition of galvanized-steel culvert in moderate environment (site 5) after six years.

Asbestos-Bonded, Asphalt-Coated, Galvanized-Steel Culvert

Minor corrosion has been noted on the rivets of the asbestos-bonded, asphalt-coated, galvanized-steel test culverts at three of the low-resistivity sites and on the wall of one of these culverts (site 10) where the asphalt coating has been removed. However, this type of culvert is performing the best of all of the types under evaluation. The panel assigned ratings of 1.0-2.2 to test culverts of this type (Table 2). It is significant that this type of culvert is withstanding corrosion so well at sites 6, 7, 9, and 10, where the effluent is brackish water with resistivity values of 350 Ω/cm and less.

Overall, the coating is deteriorating in direct proportion to the harshness of the environment, from moderate to acidic to low resistivity (Table 3). Coating ratings heavily reflect the extent to which the asphalt coating is missing from the inside and outside of the culvert.

Aluminum-Alloy Culvert

Panel ratings in Table 2 indicate that a general trend could be developing in which aluminum alloy experiences initial oxidation followed by a leveling off of this process. An obvious exception to this trend is the aluminum-alloy culvert at site 6, which has experienced extreme pitting and a perforation after six years.

The Federal Highway Administration has suggested that uncoated aluminum-alloy culverts be allowed in environments where pH values range from 4 to 9 and electrical resistivity values are greater than 500 Ω·cm (2). At test sites 4 and 8, pH values are

Table 3. Panel ratings of coatings at six years.

Coating	Moderate Environment, Site 5	Acidic Environment			Low-Electrical-Resistivity Environment							
		Site 4	Site 8	Avg	Site 1	Site 2	Site 3	Site 6	Site 7	Site 9	Site 10	Avg
12-mil coal-tar-based polymer coating	1.0	1.2	1.0	1.1	1.2	1.2	1.2	3.6	4.2	2.0	3.8	2.5
20-mil coal-tar-based polymer coating	3.0	2.2	1.6	1.9	1.2	2.8	3.2	3.8	4.8	4.2	2.5	3.2
Polyethylene coating, 10-mil interior, 3-mil exterior	1.8	2.6	2.8	2.7	1.0	1.8	2.6	4.0	4.2	4.0	-[a]	3.1
Polyethylene coating, 12-mil interior, 5-mil exterior	1.0	2.2	1.8	2.0	1.4	1.4	2.0	4.2	3.6	4.0	-[a]	2.9
Vinyl coating, 10-mil interior, 3-mil exterior[b]	1.0	1.4	1.0	1.2	1.0	1.2	1.4	3.6	4.0	3.5	4.0	2.7
Asbestos-bonded asphalt coating	1.6	1.6	3.2	2.4	3.8	3.6	2.8	1.6	1.8	3.2	3.2	2.9
Asphalt coating on galvanized steel	2.4	2.8	4.2	3.5	4.8	4.8	4.8	4.0	4.8	4.0	4.8	4.6
Asphalt coating on aluminum alloy	2.8	3.2	4.2	3.7	4.4	4.8	4.0	4.8	4.6	4.8	4.8	4.6

Note: 1 mil = 0.025 mm.
[a]No rating available; test culvert missing.
[b]Four-year ratings instead of six-year (culvert was installed two years after the other culverts).

Figure 5. Six-year panel ratings of aluminum-alloy culvert versus electrical resistivity of environment.

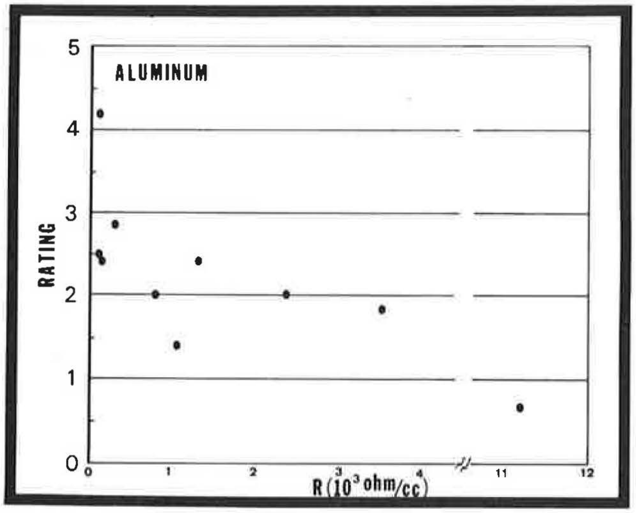
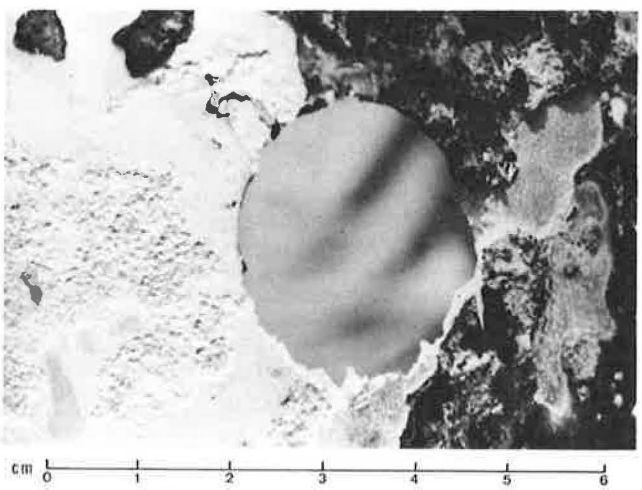


Figure 6. Pitting and thickness loss in aluminum-alloy plate arch after six years in low-resistivity environment (site 10).



Note: 1 cm = 0.39 in.

near 5, and the aluminum-alloy culverts are performing well; 5 would thus appear to be a comfortably conservative minimum value.

If one assumes that electrical resistivity can be isolated as a dominant factor in the corrosion of aluminum alloy, one can develop an interesting plot of six-year panel ratings of this culvert from Table 2 versus critical resistivity values from Table 1 (see Figure 5). The rate of corrosion among the aluminum-alloy test culverts increases as the resistivity of the environment decreases. LADOTD policy states that the aluminum-alloy culvert will be excluded from consideration when the resistivity of the surrounding soil and water is less than 1500 Ω/cm^3. This minimum level is considered to be conservative but comfortable.

Asphalt-Coated, Aluminum-Alloy Culvert

Comparison of six-year panel ratings of bare versus asphalt-coated, aluminum-alloy test culverts (Table 2) reveals that the coating has improved the corrosion-related performance of the metal culvert only slightly for two of the three environments. A similarity in the six-year ratings for bare versus asphalt-coated, aluminum-alloy culverts can be seen in a site-by-site review of Table 2.

The asphalt coating on the aluminum-alloy culverts has not proved to be sufficiently durable (Table 3). The durability that has been exhibited is greatest in the moderate environment and least in the low-resistivity environment.

Aluminum-Alloy-Plate-Arch Culvert

Panel ratings for the aluminum-alloy-plate-arch test culvert are also given in Table 2. These ratings have generally been on the borderline between good and fair except at sites 6, 7, 9, and 10 (the four brackish-water sites), where the panel has through the years noted severe pitting and thickness loss and perforation of two of the test plates.

The plate arch is not clad with another aluminum alloy as were the round aluminum-alloy pipes mentioned above. However, the aluminum-alloy plate and pipes did experience similar signs of deterioration--pitting and thickness loss. These signs are shown in Figure 6, a close-up field photograph of the plate arch at site 10.

CONCLUSIONS

1. The rate of corrosion of the galvanized-steel test culverts increases as the environment changes from moderate to acidic to low electrical resistivity. The rate of corrosion of the aluminum-alloy test culverts is similar for moderate and acidic environments and is faster in the low-electrical-resistivity environment.

2. In the moderate environment (pH = 6-8, R > 2000 Ω/cm^3), all of the test culverts are performing satisfactorily. The asbestos-bonded, bituminous-coated, galvanized-steel culvert; the bituminous-coated, aluminum-alloy culvert; the bituminous-coated, galvanized-steel culvert; and the uncoated aluminum-alloy culverts seem well suited for the acidic environments (pH = 5+, R > 2000 Ω/cm^3). The asbestos-bonded, bituminous-coated, galvanized-steel culvert stands out in its ability to resist corrosion in the low-electrical-resistivity environments (pH = 6-9, R = 0-2000 Ω/cm^3).

3. The rate of deterioration of coatings generally increases as the characterization of the environment changes from moderate to acidic to low electrical resistivity. Bituminous coating is susceptible to removal during transport and installation (especially in hot weather) and to cracking as it ages. Polymeric coatings cannot be relied on to seal moisture and air from metal culverts. Factors such as delaminations at the culvert edge undermine this ability to seal, and blisters occur. The thick asbestos-bituminous coating is the most durable of the coatings being evaluated.

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The contents of this paper reflect my views, and I am responsible for the facts and the accuracy of

the data presented. The contents do not necessarily reflect the official views or policies of the state of Louisiana or the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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Motor-Vehicle Corrosion from Deicing Salt

FRANK O. WOOD

The benefits and costs of road deicing and its resultant effects on motor vehicles are discussed. A dollar figure cannot be put on benefits such as lives saved in quicker response time to medical and fire emergencies and lives saved by reduced traffic accidents. Even without these factors, the benefit/cost ratio justifies the use of deicing salts. A carefully designed and executed test reported by the American Public Works Association appears to indicate that it is not possible to inhibit salt. Chemicals other than salt and nonchemical methods that have been considered for ice control are briefly described. Other methods, in addition to alternate deicing compounds, include Verglimit, hydrophobic substances, electrically heated pavements, earth-heated pavements and geothermal heating, urethane foam and styrofoam insulation under bridge decks, air-jet plows, high-velocity sprays of deicing chemicals, infrared heating lamps, and underbody-bladed trucks. Salt, however, continues to be the least expensive deicer. Current techniques of corrosion protection in automobile manufacture are described.

A report by the Institute for Safety Analysis on the benefits and costs of road deicing, issued in November 1976, indicates the following annual economic benefits and costs (1):

Category	Annual Economic Benefits ($000 000s)
Reduced wage losses	
Lateness to work	7 600
Work absenteeism	3 000
Reduced production losses	7 000
Reduced losses in goods shipment	600
Reduced fuel costs	200
Total	18 400

Category	Annual Costs of Road Salting ($000 000s): Institute for Safety Analysis Study (1)	Abt Associates Study (2)
Utilities	2	10
Vehicle corrosion	643	2000
Highway bridge decks	160	500
Trees and vegetation	0	50
Water supplies	10	150
Salt and application	200	200
Total	1015	2910

Among the benefits of road salting that cannot be given a dollar figure is reduced fuel consumption. The Institute for Safety Analysis report (1) cites a saving of 0.37-1.2 billion gal/year. It has been calculated, based on a study by Claffey (3), that automobiles in the Milwaukee area would consume an additional 6 million gal of gasoline per year if the streets were not maintained during the wintertime. This calculation was made in response to a proposal by Milwaukee officials that the amount of salting be reduced by 50 percent to save 200 000 gal of gasoline used to operate salt-spreader trucks.

Other benefits of deicing include the lives saved by quicker response time to medical emergencies--e.g., heart attacks, burns, poisonings, home accidents, and work accidents--and fire alarms.

Lives saved because of a reduction in traffic accidents are also not given a dollar figure. Although no precise cost can be placed on this, the Institute for Safety Analysis report (1) quotes research that shows that about 26 percent of all noninstantaneous traffic fatalities have a potential for survival. If medical care for critically injured accident victims is delayed 1 h, the percentage of those likely to survive drops to about 6.25 percent and to less than 2.5 percent in 3 h.

The estimated annual cost of vehicle corrosion in the United States is $643 million. The study by Abt Associates (2) estimates this cost to be $2 billion/year.

The traditional cost of $100/vehicle/year has been largely discounted. In fact, a task group report of the National Association of Corrosion Engineers (4) states the following:

> It has been widely quoted that corrosion damage devalues the average automobile by about $100.00 annually. The widespread use of this number is regrettable because it is not derived on the basis of an economic study. The $100.00 annual loss was simply estimated and should not have been construed in any way as being quantitative or even semi-quantitative.

The Institute for Safety Analysis study estimates that the damage to bridge decks was $160 million based on actual repair costs, whereas the Abt Associates study estimates $500 million based on repair costs and estimated time loss during bridge repair in the summertime. However, the Abt Associates study estimates that there would be no economic losses as a result of leaving snow and ice on the highways in the wintertime. The Institute