CEMENT-MORTAR LININGS FOR DUCTILE IRON PIPE

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By Richard W. Bonds, P.E.
DIPRA Research/Technical Director

Historical Development

THE FIRST CAST IRON (Gray Iron) water mains were not coated or lined, but were installed in the same condition in which they came from the molds following cleaning. After many years, it became evident that the interior of the pipe might be affected by certain types of water. The use of bituminous coatings was proposed, and most of the Gray Iron pipe sold for water works service after about 1860 was provided with a hot dip bituminous lining and coating, usually of molten tar pitch. In those systems where the water was relatively hard and slightly alkaline, bituminous linings were generally satisfactory. Where soft or acid waters were encountered, however, problems occurred — such as the water being red or rusty and/or a gradual reduction of the flow rate through the pipe. Aggressive water penetrated the pinholes in the tar coating and tuberculation ensued. The need for a better pipe lining to combat tuberculation led to experiments and research with cement mortar as a lining material.

In 1922, the first cement-lined Gray Iron pipe was installed in the water distribution system of Charleston, South Carolina. This pipe was lined by means of a projectile drawn through the pipe. Friction flow tests conducted in 1999 show that this original cement-lined Gray Iron pipe has retained a Hazen-Williams coefficient ("C" value) of 130.

Since 1922, many improvements have been made in the production of cement-lined iron pipe. Cement-mortar-lined pipes are centrifugally lined at the factory to assure that the best possible quality control is maintained and that a uniform thickness of mortar is distributed throughout the entire length of pipe. Cement linings prevent tuberculation by creating a high pH at the pipe wall, and ultimately by providing a physical barrier to the water. Cement linings are also smooth, which results in high flow coefficients. Ductile Iron pipe installed in water systems today is furnished with a cement-mortar lining unless otherwise specified by the purchaser. For existing unlined Gray Iron pipe, on-site cleaning and lining may be economically feasible to restore hydraulic capacity.

Development of Standards

From 1922 to 1929, many installations were made under various manufacturers' specifications. In 1929, ASA Sectional Committee A21 on Cast Iron Pipe issued a tentative standard for cement-mortar linings. This standard was published by AWWA as a tentative standard in 1932. After various revisions and refinements, it was officially adopted by ASA in 1939 under the designation of A21.4 (AWWA C104) "Specifications for Cement-Mortar Lining for Cast Iron Pipe and Fittings." Among other things, this standard specified the cement to be used as Portland cement, ASTM designation C-9.

During the period 1940-1952, considerable research was done on various types of cement, methods of manufacture, and methods of curing cement-mortar to improve the quality of cement-mortar linings. As a result of this research, a revised edition of the 1939 standard was approved and issued in 1953.

The centrifugal process for lining was further developed during the 1940-1952 period to provide the controls and techniques necessary to ensure uniformity of thickness throughout the length of a pipe. Another major revision in the 1953 edition was the recognition of the ability of asphaltic seal-coat materials to provide controlled curing of the mortar. The use of this method was permitted as a substitute for the moist-curing process.

A revised third edition was approved and issued in 1964. The 1964 standard reduced the minimum permissible thickness of the lining. The reduction was based on more than 20 years of Cast Iron Pipe Research Association (CIPRA) studies of experimental test lines having cement-mortar linings ranging from 1/32-inch to 1/4-inch in thickness, on field tests of linings of these thicknesses that had been in service for more than 30 years, and on the assurance of uniformity of thickness afforded by improvements in the centrifugal lining process. Since then, the service histories of countless other installations have demonstrated the efficacy of the present cement-mortar lining thicknesses. The 1964 revision also required the cement to meet the requirements of ASTM C150, "Specification for Portland Cement."

The 1971 revision incorporated a standard test for toxicity of the seal-coat material. In the 1974 revision, major changes were made in the section on lining quality. The 1980 revision, which included metric conversions of all dimensions and physical requirements, also included the projection method as an allowable means of lining pipe and fittings. No major revisions were made in the 1985 and 1990 editions.

The 1995 revision expanded the section on cement to include types of cement other than Portland, expanded the size range to include 3-inch through 64-inch pipe, allowed the manufacturer the option of providing the cement-mortar lining with or without a seal-coat unless otherwise specified, and deleted the option of using seal-coat materials other than an asphaltic material.

The 2003 revision deleted the requirement that the cement-mortar thickness be determined while the mortar was wet.

Asphaltic Seal-coat

The use of a seal-coat was first introduced in the 1953 edition of ANSI/AWWA C104/A21.4. Research conducted by the Cast Iron Pipe Research Association from 1940 to 1952 showed that a thin asphaltic paint coating, applied to the freshly placed cement-mortar lining, would greatly minimize moisture loss during hydration, thereby resulting in controlled cure of the mortar. Thus, this method was permitted as a substitute for the moist-curing process. Experience later showed that seal-coat also provided a secondary benefit in that, as a barrier coating, it helped retard leaching of the cement by soft, aggressive waters.

From 1953 to 1995 ANSI/AWWA C104/A21.4 required the cement-mortar lining to be given a seal-coat of asphaltic material unless otherwise specified. The 1995 edition of the standard, however, was revised to allow the manufacturer the option of providing the cement-mortar lining with or without a seal-coat unless otherwise specified.

One of the primary reasons for the change was to minimize the use of seal-coat and thereby help reduce air pollution. The seal-coat material used on Ductile Iron pipe and

There are two methods of cement lining Ductile Iron pipe. In the projection method, shown here, mortar is sprayed on the pipe wall by a rapidly revolving head inserted through the center of the stationary pipe. The pipe is then rotated slowly and vibrated to smooth the lining.

Sylvia Caswell

fittings is a solvent-base asphaltic paint that contains volatile organic compounds (VOCs). This is not a concern from the standpoint of any health effects associated with seal-coat materials in contact with potable water. All seal-coat materials presently used on Ductile Iron pipe and fittings have been tested and certified as being in compliance with ANSI/NSF Standard 61, "Drinking Water System Components — Health Effects." However, emissions of VOCs during application and curing of the seal-coat is a concern. The Clean Air Act placed strict restrictions on emissions of numerous air pollutants, including VOCs. In light of that, manufacturers and users of coatings are continually developing alternative coatings that contain little or no VOCs. In considering the alternatives, along with the fact that there were other manufacturing techniques for curing the mortar, the option of eliminating the seal-coat was adopted.

Also, the practice of applying a seal-coat to the cement-mortar linings in Ductile Iron pipe and fittings has been somewhat unique to the United States. Elsewhere in the world, cement-lined Ductile Iron pipe and fittings are typically furnished without a seal-coat. Only a few locations in this country have sufficiently aggressive waters to necessitate the use of a seal-coat. In these few locations, leachates from the uncoated cement lining can cause an undesirable rise in the pH of the water, particularly under low flow conditions in small-diameter pipe. For this reason, the seal-coat was retained as an optional requirement of the standard.

Examination of numerous cement linings following years of service in various types of water has shown that high flow characteristics have been maintained by both seal-coated linings and uncoated linings.

Cement-mortar linings are normally acceptable for service up to the boiling point of water; however, because of the softening point of asphaltic seal-coat, the temperatures of seal-coated linings should not exceed 150°F. These temperature limitations are intended as general guidelines and may not be applicable under all conditions. If higher service temperatures are to be encountered, the manufacturer should be consulted for specific recommendations.

Lining Processes

Both the centrifugal process and the projection method of applying cement-mortar linings are used in modern practice. By using these methods, excellent quality control of the cement-mortar and lining operation can be maintained. The linings produced are smooth, uniform, and meet the rigid requirements of ANSI/AWWA C104/A21.4, "Cement-Mortar Lining for Ductile-Iron Pipe and Fittings for Water." The thickness of the linings for pipe and fittings, as stated in this standard, shall not be less than $^{1}/_{16}$-inch for 3 to 12-inch pipe; $^{3}/_{32}$-inch for 14 to 24-inch pipe; and $^{1}/_{8}$-inch for 30 to 64-inch pipe. Double thickness linings with thicknesses twice those listed above can be furnished if specified on the purchase order by the buyer.

The centrifugal process of applying mortar inside a Ductile Iron pipe consists of distributing the mortar evenly throughout the length of the pipe by means of a moving lance while the pipe is spinning at a relatively low speed. The projection method consists of spraying or slinging mortar evenly onto the pipe wall by a rapidly revolving moving head that has been inserted through the stationary pipe at its center.

After the mortar is applied by one of the above methods, it can be smoothed and compacted by either of two methods, depending on pipe size and equipment being used. The pipe may be spun at a high rate accompanied by vibration to produce a dense lining which adheres well to the pipe wall. This high-speed spinning brings water and fine cement particles to the lining surface, which necessitates washing to remove. Conversely, the pipe may be spun at a lower rate, also accompanied by vibration to smooth and compact the lining. This rotational rate is not high enough to bring excess water and fine particles of cement to the surface; thus there is no need to wash the lining as is the case with the high-speed centrifugal process.

The linings produced by each of these

Ductile Iron pipe without a seal-coat lies ready for shipment. Eliminating the seal-coat is now an option for manufacturers unless otherwise specified.

methods are dense, smooth, and offer very little frictional resistance to the flow of water. Fittings are lined by the projection method or by hand application.

To provide for proper curing of cement linings in pipe by preventing too rapid a loss of moisture from the mortar, the lining can be (a) stored in a moist atmosphere for a period of time, (b) processed through an elevated temperature "curing tunnel" to accelerate the cure, or (c) seal-coated immediately. The adherence of the cement lining to the wall of the pipe is such that the pipe may be cut and tapped without concern for damage to the lining.

Properties of Cement Linings

The protective properties of cement linings are due to two properties of cement. The first is the chemically alkaline reaction of the cement and the second is the gradual reduction in the amount of water in contact with the iron. When a cement-lined pipe is filled with water, water permeates the pores of the lining, thus freeing a considerable amount of calcium hydrate. The calcium hydrate reacts with the calcium bicarbonate in the water to precipitate calcium carbonate, which tends to clog the pores of the mortar and prevent further passage of water. The first water in contact with iron through the lining dissolves some of the iron, but free lime tends to precipitate the iron as iron hydroxide, which also closes the pores of the cement. Sulfates are also precipitated as calcium sulfate. Through these reactions, the lining provides a physical as well as a chemical barrier to the corrosive water.[1]

Autogenous Healing

Cracks and lack of lining adherence in pipe and fittings have occasionally been detected prior to installation. These can occur due to shrinkage of linings, temperature variations, and improper handling. In some instances, there have been concerns that the lining would not provide the protection for which it was intended or that it might be dislodged by the flow of the water. Neither of these concerns is justified. Tests conducted by Wagner and reported in an article published in the June 1974 *Journal AWWA* show that lining fissures, developed while in storage, will heal themselves when put in contact with either flowing or non-flowing water.[2]

Cement-mortar linings have been applied to Gray Iron and Ductile Iron pipe for more than 82 years. DIPRA is not aware of any performance problems that have occurred due to cracks or loose cement-mortar linings as long as the lining was intact before placing the line in service.

Cracks in cement linings are generally of two types. One is a surface crazing occurring as a checkerboard or cobweb pattern of hairline cracks. This surface crazing occurs only in the fine sand and cement particles that cover the homogeneous layer of dense mortar. This outer skin is the first exposed to hydration and thus, may develop a network of fine surface cracks. These hairline cracks affect only the surface and are not detrimental to the serviceability of the lining. ANSI/AWWA C104/A21.4 permits this type of crack without limitation. The other type of cracking is circumferential or longitudinal. Circumferential cracking may extend completely around the pipe and may cause slight disbondment of the lining. Although the standard allows circumferential cracks of any length, it limits the length of longitudinal cracks. Loose areas of cement-mortar linings are permitted by the standard as long as the lining is intact.

When a cement-lined pipe is placed in service and filled with water, some water is absorbed by the lining. Water is absorbed, not only into the pores and voids in the mortar, but also into the capillary channels of the calcium silicate gel. The ultimate result of this water absorption is that the lining swells practically to its initial volume. Thus, the lining is restored to intimate contact with the pipe wall and the cracks in the lining are closed. Because this swelling process is relatively slow, it may take up to several weeks for the lining to be completely restored to its initial volume.

Not only will the cracks close and the lining become tight after a period of exposure to water, but also the cement will eventually knit back together. This occurs by a process known as autogenous healing, a phenomenon long recognized by the concrete industry, which occurs due to the formation of calcium carbonate and the continuing hydration of cement grains in the lining. Any cracks that might remain slightly open due to inadequate swelling are subsequently closed by the formation of calcium carbonate.

Field Repair of Damaged Cement Linings

Cement lining will withstand normal handling; nevertheless, pipe or fittings may be found at times to have damaged linings that should be repaired before being placed in service.

ANSI/AWWA C104/A21.4 provides that damaged lining may be repaired, and the following repair procedure is recommended:

1. Cut out the damaged lining to the metal so that the edges of the lining not removed are perpendicular or slightly undercut.
2. Clean the damaged area and adjoining lining.
3. Prepare a stiff mortar from a mixture of cement, sand, and water. The cement-mortar shall contain not less than one part cement to two parts sand, by volume. (Field experience has shown that

a one-to-one ratio of cement to sand provides excellent results.)

4. Thoroughly wet the cut-out area and adjoining lining.
5. Apply the mortar and trowel smooth with the adjoining lining.
6. The repaired lining should be kept moist by tying canvas or wet burlap over the ends of the pipe or fitting for at least 24 hours. (If the repair area is small, it can be covered with a wet cloth.) As an alternative, the repaired lining may be seal-coated with a cut-back type of asphaltic seal coating. This should be sprayed or brushed on within five to 30 minutes after the mortar is applied.

Proper curing of the repair is important to ensure a properly hydrated mortar that is hard and durable. Too rapid a loss of moisture from the repair due to hot weather or high wind will delay proper curing. In cold weather, the patched area should be protected from freezing.

Flexural Behavior

Ring bending tests have been performed on full-length cement-mortar-lined pipe to check its behavior under backfill loads.[3] These tests revealed that the cement-mortar-lining failure and subsequent spalling occurred on the sides of the pipe (at the 3 o'clock and 9 o'clock locations) due to compression with deflections in the range of 6 to 12 percent of the initial diameter. ANSI/AWWA C150/A21.50 (Thickness Design of Ductile-Iron Pipe) has limited the maximum allowable deflection of the pipe ring section to 3 percent. This results in a safety factor of at least 2, and sometimes as high as 4.

Abrasion-resistance

Parameters involved in the abrasion phenomenon include flow velocity; the amount of solid particles; the size, shape, and hardness of the particles; the type of flow (turbulent or laminar); surface roughness and hardness of the lining; and the number of fittings per mile. Although the relative influence of these factors can be reasonably appreciated, there is no known equation able to predict abrasion resistance of different pipe materials in various situations. Inevitably, abrasion will occur at locations of changes in direction before it will occur along the length of a pipe barrel.

The abrasive characteristics of potable water are slight since this type of water contains limited amounts of solids and normally has velocities ranging from 2 to 10 fps. Cement-mortar-lined pipes in drinking water service for more than 82 years show no evidence of internal abrasion. In the absence of long-term laboratory testing, the available literature lists satisfactory performance for cement/cement-mortar linings for potable water with velocities of 20 to 40 fps. However, one has to realize that all installations do not perform the same. Different installations will have different configurations, bend angles, flow characteristics, amount and shape of solids content in the water, etc. Using a velocity of 20 fps and applying a safety factor of 2, remembering that the kinetic energy of a particle is a function of the square of the velocity, will result in a velocity of 14 fps. This should normally be a good conservative maximum design velocity for continuous service for most applications. Please contact DIPRA member companies when velocities greater than 14 fps are anticipated.

Cement-mortar linings' resistance to abrasion is more important in drainage and sewage pipelines where solid particles are present. In these applications, the size, shape, and hardness of the particles will greatly influence the abrasion rate. Again, cement-mortar-lined pipe continues to perform satisfactorily in this type of service.

Resistance to Soft and Acidic Waters

Waters carry varying amounts of different ions resulting from the disassociation of soluble salts found in soils. Waters that have a very low ion content are aggressive to calcium hydroxide contained in hydrated cements due to the waters' low content of carbonates and bicarbonates. Soft waters may also have acidic characteristics due to the presence of free CO_2.

When cement-mortar linings are subjected to very soft water, calcium hydroxide, $CA(OH)_2$, is leached out. The concentration of leachates increases with the aggressiveness of the water and its residual time in the pipe and is inversely proportional to the diameter of the pipe. These waters will also attack calcium silicate hydrates, which form the larger portion of cement hydrates. Although calcium silicate hydrates are almost insoluble, soft waters can progressively hydrolyze them into silica gels, resulting in a soft surface with reduced mechanical strength.

Seal-coat will retard this leaching and attack to a great extent; however, as mentioned before, there are very few locations in this country that have sufficiently aggressive waters to necessitate the use of a seal-coat. Also, such aggressive waters may cause toxic metals to leach from piping in customers' homes, making it difficult to pass water quality standards requiring tests at first draw from customers' taps. Therefore, water quality standards requiring better balanced water chemistry may cause these few communities to treat their water, and further diminish the need for seal-coat.

Utilities or municipalities who are concerned that their water may be aggressive to cement-mortar linings without a seal-coat are encouraged to follow the procedure detailed in Section II.A., "Use of Seal-Coat," in the Foreword to the ANSI/AWWA C104/A21.4 Standard to determine if a cement-mortar lining, without seal-coat, will impart objectionable hardness or alkalinity to the water.

DIPRA is not aware of any potable water distribution system in the United States where standard cement-mortar-lined Ductile Iron pipe is not applicable although a few may necessitate the use of a seal-coat. Cement-mortar-lined Ductile Iron pipe is generally considered to be suitable for continuous use at pH between 4 and 12 for seal-coated linings, and between 6 and 12 for non-seal coated linings. For service with pH outside this range, consult DIPRA member companies.

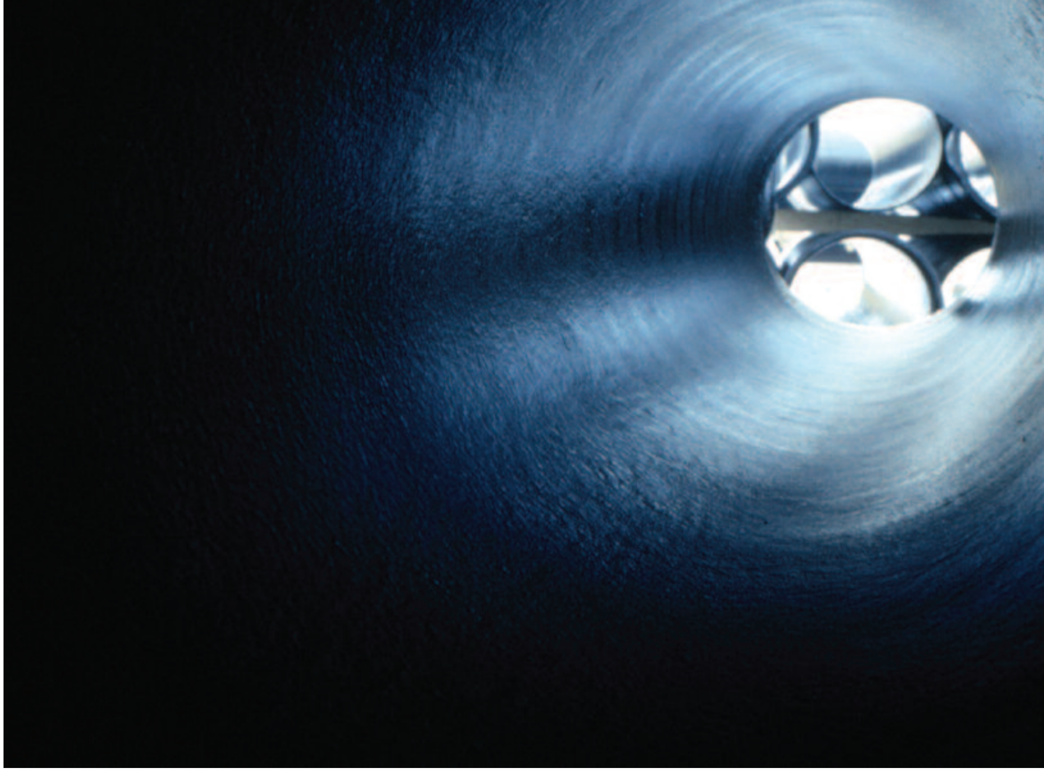
Flow Test Results on Cement-mortar-lined Ductile and Gray Iron Pipe

Friction head loss or drop in pressure in a pipeline is an everyday concern for the water works engineer. Head-loss calculations are based on equations developed by hydraulic engineers after conducting numerous flow tests on actual working water mains. Several formulas were developed by Darcy, Chezy, Cutter, Manning, Hazen-Williams, and others. Of these, the formula and tables prepared by Hazen-Williams have proved to be the most popular.

A pipe lining, to be satisfactory, must provide a high Hazen-Williams flow coefficient "C" initially and must have sufficient durability to maintain a high flow coefficient over many years of service. Unless the lining meets the above requirement, its other properties, chemical or physical, are of little significance. Numerous flow tests have been made on operating lines throughout the United States to determine how well cement-mortar linings meet these basic requirements. Tests on both new and old water mains have established the average value of "C" that can be expected of new cement-lined iron pipe and have also provided a measure of the continued effectiveness of such linings over extended periods of service.

Table 1 presents the results obtained

Cement-mortar-lined Ductile Iron pipe has a Hazen-Williams "C" value of 140, a realistic value that is maintained over time.



from a number of friction flow tests made on new, or relatively new, cement-lined iron pipe. The average value of "C" for new pipe of 4-inch through 36-inch diameter was found to be 144.

Over the years, DIPRA has conducted a series of flow tests on cement-lined Gray and Ductile Iron pipes which have been in service for extended periods of time in water distribution systems across the country. The purpose of the tests has been to determine whether cement lining continues to provide protection against deterioration of the hydraulic capacity of the pipes after varying periods of time and in varying water-quality conditions.

Taking into account the effect of unknowns in making such tests on operating systems (i.e., fittings, service connections, and other hydraulic obstructions), the test results in Table 2 show that cement-mortar lining is an effective means of protecting Gray and Ductile Iron piping from the effects of aggressive water. Even the oldest pipes carrying the most aggressive waters continue to exhibit "C" values in the same range as new cement-lined pipe. Recent test results reconfirm the conclusions of several earlier series of tests performed 40 to 50 years ago.

Flow Coefficient of Cement-mortar-lined Ductile Iron Pipe

For laminar, fully developed flow in a pipe, friction depends only on the Reynolds number (a function of velocity, inside pipe diameter, and the kinematic-viscosity of the fluid being transported). It is interesting to note that the roughness of the pipe wall is not considered. The reason is that, for the parabolic laminar flow velocity profile, very little of the flow comes in contact with the roughness elements of the wall surface; the velocities in the vicinity of the wall surface are quite low. When laminar flow exists, the fluid seems to flow as several layers, one on another. Because of the viscosity of the fluid, a shear stress is created between the layers of the fluid. Energy is lost from the fluid by the action of overcoming the frictional force produced by the shear stress.

For turbulent flow of fluids in circular pipes, there is a layer of laminar flow adjacent to the pipe wall called the laminar sublayer. Even in turbulent boundary layers there will be this sublayer where laminar effects predominate. In the case of a pipe, the greater the Reynolds number, the thinner the laminar sublayer is. It has already been noted that the roughness has no effect on the head loss for laminar flow. If the laminar sublayer is thicker than the roughness of the pipe wall, then the flow is hydraulically smooth and the pipe has attained the ultimate in hydraulic efficiency. If this flow was plotted on the Moody diagram, it would coincide with the "smooth pipe" curve.

Shortly after cement-mortar linings were introduced for Gray Iron pipe, tests were conducted at the hydraulic laboratory of the University of Illinois on 4-, 6-, and 8-inch Gray Iron pipe. Hazen-Williams coefficients were calculated for each pipe size and at the extremes of the testing range — namely, 2 and 10 fps. The test results reported Hazen-Williams coefficients ranging from 150 to 157. Taking these laboratory findings and calculating the Darcy-Weisbach friction coefficient for the extremes of the test range and plotting them on the Moody diagram, the plotted points generally conform to the curve for "smooth pipes." This demonstrates that centrifugally applied cement-mortar lining, since first introduced into the marketplace, has attained the ultimate in hydraulic efficiency. No "smoother" pipe can be produced. To suggest that a "smoother" pipe is available requires stepping outside the bounds of modern hydrodynamics. Some people may have difficulty accepting this fact because they think in terms of smoothness to the touch instead of hydraulic smoothness. So long as the "roughness" of the pipe wall remains well submerged in the laminar sublayer, the flow will be hydraulically smooth.

DIPRA and its predecessor, CIPRA, have long advocated a Hazen-Williams "C" value of 140 for use with cement-lined Gray and Ductile Iron pipe. This recommendation of a "C" value of 140 for design purposes is sound. It recognizes that the real world of pipelines is a far cry from the gun-barrel geometry of the laboratory pipeline. Furthermore, DIPRA's continued field testing of operational pipelines has shown a "C" value of 140 to be realistic, and one that is maintained over time — even when transporting highly aggressive waters.

The Effect of a Larger Inside Diameter

Some substitute pipe manufacturers recommend a Hazen-Williams flow coefficient higher than 140 for their products. The implication is clear — a substitute material will create less head loss than cement-mortar-lined Ductile Iron pipe. Nothing could be further from the truth.

In all normally specified pipe sizes, cement-mortar-lined Ductile Iron pipe has an internal diameter that is larger than the nominal diameter, which is larger than the nominal pipe size. For most substitute pipe materials, the inside diameter is equal to — or in some cases, even less than — the nominal pipe size. The head loss encountered in a piping system is much more sensitive to available pipe inside diameters than normal flow coefficients. For example, 6,000 gpm flowing through 24-inch diameter pipe, PVC DR 18 (assuming a "C" value of 150) would develop 37.6 percent more head loss than that flowing through Pressure Class 200 cement-mortar-lined Ductile Iron pipe (assuming a "C" value of 140).

Conclusion

Cement-mortar-lined Ductile Iron pipe has a service record unequalled in the water works industry. Since first field-applied to Gray Iron pipe in 1922, cement-mortar lining has undergone numerous manufacturing improvements.

Today, cement-mortar lining is applied either by the centrifugal process or the projection method, thus maintaining excellent quality control of the cement-mortar and lining operation. The linings produced by these methods are dense, smooth, and offer very little frictional resistance to the flow of water.

Cement-mortar-lined Ductile Iron pipe provides a Hazen-Williams flow coefficient, or "C" value, of 140 — a realistic value that is maintained over the life of the pipe. This standard lining, which is furnished in accordance with ANSI/AWWA C104/A21.4, continues its tradition of dependable, trouble-free service.

References

[1] Helton, B., "Cracks and Looseness in Cement Linings of Cast Iron and Ductile Iron Pipe and Fittings," unpublished.

[2] Wagner, E.F., "Autogenous Healing of Cracks in Cement-Mortar Linings for Gray-Iron and Ductile-Iron Water Pipe," *Journal AWWA*, June 1974.

[3] Kennedy, Jr., H., "The New Ductile Iron Pipe Standards," *Journal AWWA*, November 1976.

Table 1

Flow Tests of Cement-mortar-lined Gray and Ductile Iron Pipe

Location	Size Inches	Length Feet	Age Years	Hazen-Williams C
Alma, MO	6	23,800	1	137
Birmingham, AL	6	473	new	147
Bowling Green, OH	20	45,600	1	143
Casper, WY	12	500	new	141
Charleston, SC	6	300	new	145
Chicago, IL	36	7,200	1	147
Cleveland, TN	20	31,400	2	144
Colorado Springs, CO	20	7,000	3	137
Concord, NH	14	500	new	151
Copperas Cove, TX	8	28,100	1	144
Corder, MO	8	21,400	1	145
Corpus Christi, TX	36	74,000	new	145
Fitchburg, MA	20	500	1	142
Gary, IN	20	8,000	1	140
Greensboro, NC	30	848	3	148
Hartford, CT	16	800	1	149
New Orleans, LA	12	37,300	1	141
Newton, IA	20	27,300	1	144
Safford, AZ	10	23,200	2	145
Simpsonville, SC	16	27,700	1	137
St. Louis, MO	30	17,700	new	151
Univ. of Illinois	6	400	new	151
Green Bay, WI	16	1,149	1	138

Table 2

Flow Tests of Cement-mortar-lined Gray and Ductile Iron Pipe After Extended Periods of Service

Location	Size Inches	Length Feet	Age Years	Hazen-Williams C
Baltimore, MD	12	909	18	136
Birmingham, AL	6	473	6	141
	6	473	14	138
	6	473	17	133
Catskill, NY	16	30,825	25	136
Champaign, IL	16	3,920	12	137
	16	3,920	22	139
	16	3,920	28	145
	16	3,920	36	130
Charleston, SC	6	300	12	146
	6	300	16	143
	8	300	51	131
	8	300	59	130
	8	300	77	130
	12	500	15	145
	12	500	25	136
Chicago, IL	36	7,200	12	151
Concord, NH	12	500	13	143
	12	500	29	140
	12	500	36	140
Danvers, MA	20	500	31	135
	20	500	38	133
Greenville, SC	30	87,400	13	148
	30	87,400	20	146
	30	50,700	19	148
	30	50,700	25	146
Greenville, TN	12	500	13	134
	12	500	29	137
	12	500	36	146
Knoxville, TN	10	500	16	134
	10	500	32	135
	10	500	39	138
Manchester, NH	12	550	5	142
	12	550	21	135
	12	1,955	45	133
Memphis, TN	10	1,070	31	135
Orange, CA	6	1,004	26	140
Safford, AZ	10	23,200	16	144
S. Burlington, VT	24	1,373	8	138
Seattle, WA	8	2,686	29	139
Tempe, AZ	6	1,235	24	144
Tacoma, WA	8	2,257	16	136
Wister, OK	18	3,344	30	139

DIPRA MEMBER COMPANIES

American Cast Iron Pipe Company
P.O. Box 2727
Birmingham, Alabama 35202-2727

Atlantic States Cast Iron Pipe Company
183 Sitgreaves Street
Phillipsburg, New Jersey 08865-3000

Canada Pipe Company, Ltd.
1757 Burlington Street East
Hamilton, Ontario L8N 3R5 Canada

Clow Water Systems Company
P.O. Box 6001
Coshocton, Ohio 43812-6001

McWane Cast Iron Pipe Company
1201 Vanderbilt Road
Birmingham, Alabama 35234

Pacific States Cast Iron Pipe Company
P.O. Box 1219
Provo, Utah 84603-1219

United States Pipe and Foundry Company
P.O. Box 10406
Birmingham, Alabama 35202-0406

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245 Riverchase Parkway East, Suite O
Birmingham, Alabama 35244-1856
Telephone 205 402-8700 FAX 205 402-8730
http://www.dipra.org

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Published 12-89
Revised 3-05