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Reaffirmed without revision 2019*

AWWA Standard

Design of Prestressed Concrete Cylinder Pipe

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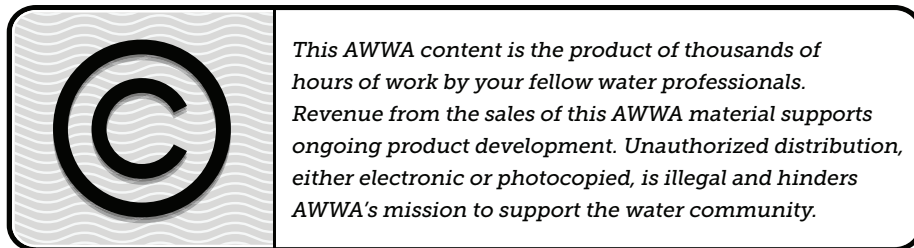
AWWA Standard

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Foreword

This foreword is for information only and is not a part of ANSI/AWWA C304.

I. Introduction.

I.A. *Background.* This standard establishes the mandatory minimum requirements for the structural design of prestressed concrete cylinder pipe (PCCP) and provides procedures that will ensure that the design requirements are satisfied.

There are two types of PCCP: (1) lined-cylinder pipe (LCP), with a core composed of a steel cylinder lined with concrete, which is subsequently prestressed with high-tensile wire wrapped directly around the steel cylinder; and (2) embedded-cylinder pipe (ECP), with a core composed of a steel cylinder encased in concrete, which is subsequently prestressed with high-tensile wire wrapped around the exterior concrete surface. The cores of both types of pipe are coated with portland-cement mortar.

Before the procedures and requirements contained in this document were developed, the design of PCCP was determined by two distinct procedures. These were designated methods A and B described in appendixes A and B of ANSI/AWWA C301-84, *Prestressed Concrete Pressure Pipe, Steel-Cylinder Type, for Water and Other Liquids*.

Method A used a semiempirical approach based on (1) W_o , which is nine-tenths of the three-edge bearing test load that causes incipient cracking; and (2) the theoretical hydrostatic pressure, P_o , which relieves the calculated residual compression in the concrete core as a result of prestressing. The allowable combinations of three-edge bearing load and internal pressure were determined by a cubic parabola, passing through W_o and P_o , which defined the limits of these combinations. The three-edge bearing loads used in method A were converted to earth loads and transient external loads using bedding factors provided in AWWA Manual M9, *Concrete Pressure Pipe* (1979) and in the ACPA[†] *Concrete Pipe Design Manual* (1988).

Method B was based on a procedure that limited the maximum combined net tensile stress in pipe under static external load and internal pressure to a value equal to $7.5 \sqrt{f'_c}$, where f'_c = the 28-day compressive strength of core concrete in psi ($0.62 \sqrt{f'_c}$, where f'_c = the 28-day compressive strength of core concrete in MPa).

Both design methods limited the working pressure to P_o for ECP and to $0.8P_o$ for LCP, where P_o was the internal pressure required to overcome all compression in

* American National Standards Institute, 25 West 43rd Street, Fourth Floor, New York, NY 10036.

† American Concrete Pipe Association, 1303 West Walnut Hill Lane, Suite 305, Irving, TX 75038.

the core concrete excluding external load. Under transient conditions, such as those produced by surge pressures and live loads, both methods permitted increased internal pressure and external load.

Although the two methods of design produced similarly conservative results that served PCCP users well for nearly half a century, a unified method of design, described in this standard, was developed to replace methods A and B.

The following objectives for the unified design procedure were established:

1. It should replace both existing methods, the semiempirical method A and the working stress method B, described in ANSI/AWWA C301-84.
2. It should be based on state-of-the-art procedures for the design and analysis of concrete and prestressed concrete structures.
3. It should account for the state of prestress in the pipe, as well as the combined effects of external loads, pipe and fluid weights, and internal pressures.
4. It should agree with the results of 40 years of experimental data gathered by the American concrete pressure-pipe industry.
5. It should preclude the onset of visible cracking under working plus transient conditions.
6. It should provide adequate safety factors based on elastic and strength limit states.

The method of calculating residual stresses in the concrete core, the steel cylinder, and the prestressing wire was updated to separately account for the effects of elastic deformation, creep, and shrinkage of concrete, and the relaxation of the prestressing wire (Zarghamee, Heger, and Dana 1988a; see appendix B). Intrinsic wire relaxation, creep factors, and shrinkage strains obtained from procedures recommended by ACI* Committee 209 (1982) (ACI 1982; see appendix B) were used in a step-by-step integration procedure (Zarghamee 1990; see appendix B) to evaluate the time-related variations of stress in the pipe elements. The results of the step-by-step integration procedure, applied to pipe in a buried environment, were used to develop simplified equations for practical design use.

Calculations of the design creep factor and shrinkage strain for buried pipe are based on the procedures recommended by ACI Committee 209. Creep and shrinkage are computed as functions of time, relative humidity, volume-to-surface ratio, age at loading, curing duration, concrete composition, and method of placement. Design values for creep factor and shrinkage strain are based on a 50-year exposure of pipe to the

* American Concrete Institute, 38800 Country Club Drive, Farmington Hills, MI 48331.

environment to which typical pipe will be exposed. The default environment is given in the following scenario:

1. The pipe is initially stored outdoors for 270 days.
2. The pipe is buried and kept empty for 90 days.
3. The pipe is filled with water for the duration of its design life.

The periods of time given in items 1 and 2 above may be extended at the purchaser's discretion.

The design wire-relaxation factor was obtained by measuring the intrinsic loss of prestressing wire, manufactured in accordance with ASTM* A648, Specification for Steel Wire, Hard Drawn for Prestressing Concrete Pipe, under constant strain and accounting for the reduction in relaxation loss caused by creep and shrinkage.

The simplified procedure, which separately accounts for concrete creep and shrinkage and wire relaxation, complies with test results (Zarghamee, Fok, and Sikiotis 1990; see appendix B) and with prior design practice (Zarghamee, Heger, and Dana 1988b; see appendix B).

The method adopted for determining allowable combinations of internal pressure, external loads, and pipe and fluid weights is based on satisfying certain limit-states design criteria (Heger, Zarghamee, and Dana 1990; see appendix B). The purpose of using limit-states design is to ensure the serviceability of pipe for design loads and working plus transient pressures and the safety of pipe against loss of prestress and failure for loads and pressures beyond the serviceability limits.

The limit-states design procedure is based on limiting circumferential thrust and bending moment resulting from internal pressure, external loads, and pipe and fluid weights. The procedure specifies that certain limit-states design criteria are not exceeded when the pipe is subjected to working loads and pressures and to working plus transient loads and pressures.

In the design procedure, three sets of limit-states criteria are used: serviceability, elastic, and strength. To satisfy the three sets of limit-states criteria, combined loads and pressures corresponding to each of these limit states must be calculated. As a result, the combined moments and thrusts in the pipe wall corresponding to the limit states must be calculated, and both uncracked and cracked cross sections must be considered. For accurate calculation of these combined moments and thrusts, the constitutive properties of concrete and mortar in tension must be expressed correctly. A

* ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

trilinear model for stress–strain relationships of concrete and mortar was adopted for use in the limit-states design of PCCP.

Serviceability limit-states criteria are intended to preclude microcracking in the core and to control microcracking in the coating under working loads and pressures. These criteria are also intended to preclude visible cracking in the core and the coating under working plus transient loads and pressures. Criteria are provided for the following:

1. Core-crack control.
2. Radial-tension control.
3. Coating-crack control.
4. Core-compression control.
5. Maximum pressure.

Elastic limit states are defined to limit combined working plus transient loads and pressures so that if cracks develop in a prestressed pipe under the transient condition, the pipe will have an elastic response, preventing damage or loss of prestress. Criteria are provided for the following states:

1. Wire-stress control.
2. Steel-cylinder–stress control.

Strength limit states are defined to protect the pipe against yielding of the prestressing wire, crushing of the concrete core under external load, and tensile failure of the wire under internal pressure. Safety factors are applied to loads and pressures that produce the strength limit states. The following criteria are provided:

1. Wire yield-strength control.
2. Core compressive-strength control.
3. Burst-pressure control.
4. Coating bond-strength control.

The limit-states design procedure for PCCP subjected to the combined effects of internal pressure, external loads, and pipe and fluid weights

1. Is a rational procedure based on state-of-the-art structural engineering practice for concrete structures.
2. Uses parameters resulting from many tests of prestressed concrete pipe and its constitutive materials.
3. Is substantiated by the results of combined-load and three-edge bearing verification tests of LCP and ECP.

The standard includes tables of standard designs for prestressed concrete LCP and a design example for ECP.

I.B. *History.* The AWWA Standards Committee on Concrete Pressure Pipe supported a recommendation that a design standard be developed for PCCP to be manufactured in accordance with ANSI/AWWA C301, Prestressed Concrete Pressure Pipe, Steel-Cylinder Type, for Water and Other Liquids. On June 20, 1989, the C301 Design Subcommittee first met for the purpose of developing the design standard. At its October 1989 meeting, the AWWA Standards Council authorized a separate design standard for PCCP. The first edition of this standard, ANSI/AWWA C304, Design of Prestressed Concrete Cylinder Pipe, was approved by the Board of Directors on June 18, 1992. Subsequent editions were approved on Jan. 24, 1999, and Jan. 21, 2007. This edition was approved by the AWWA Board of Directors on Jan. 19, 2014, and it was reaffirmed without revision on Oct. 28, 2019.

I.C. *Acceptance.* In May 1985, the US Environmental Protection Agency (USEPA) entered into a cooperative agreement with a consortium led by NSF International (NSF) to develop voluntary third-party consensus standards and a certification program for direct and indirect drinking water additives. Other members of the original consortium included the Water Research Foundation (formerly AwwaRF) and the Conference of State Health and Environmental Managers (COSHEM). The American Water Works Association and the Association of State Drinking Water Administrators (ASDWA) joined later.

In the United States, authority to regulate products for use in, or in contact with, drinking water rests with individual states.* Local agencies may choose to impose requirements more stringent than those required by the state. To evaluate the health effects of products and drinking water additives from such products, state and local agencies may use various references, including

1. An advisory program formerly administered by USEPA, Office of Drinking Water, discontinued on Apr. 7, 1990.
2. Specific policies of the state or local agency.
3. Two standards developed according to NSF:† NSF/ANSI 60, Drinking Water Treatment Chemicals—Health Effects, and NSF/ANSI 61, Drinking Water System Components—Health Effects.
4. Other references including AWWA standards, *Food Chemicals Codex*, *Water Chemicals Codex*,‡ and other standards considered appropriate by the state or local agency.

* Persons outside the United States should contact the appropriate authority having jurisdiction.

† NSF International, 789 North Dixboro Road, Ann Arbor, MI 48105.

‡ Both publications available from National Academy of Sciences, 500 Fifth Street, NW, Washington, DC 20001.

Various certification organizations may be involved in certifying products in accordance with NSF/ANSI 61. Individual states or local agencies have authority to accept or accredit certification organizations within their jurisdictions. Accreditation of certification organizations may vary from jurisdiction to jurisdiction.

Annex A, “Toxicology Review and Evaluation Procedures,” to NSF/ANSI 61 does not stipulate a maximum allowable level (MAL) of a contaminant for substances not regulated by a USEPA final maximum contaminant level (MCL). The MALs of an unspecified list of “unregulated contaminants” are based on toxicity testing guidelines (noncarcinogens) and risk characterization methodology (carcinogens). Use of Annex A procedures may not always be identical, depending on the certifier. ANSI/AWWA C304 does not address additive requirements. Thus, users of this standard should consult the appropriate state or local agency having jurisdiction in order to

1. Determine additive requirements, including applicable standards.
2. Determine the status of certifications by all parties offering to certify products for contact with, or treatment of, drinking water.
3. Determine current information on product certification.

II. Special Issues. The information needed for selection of designs from the tables of standard designs includes:

1. Inside diameter of pipe (in. [mm]).
2. Internal working pressure (psi [kPa]).
3. Type of standard bedding.
4. Height of earth cover over the pipe (ft [m]).

The standard criteria used in the design selection tables are summarized in Sec. 9.4 preceding the design selection tables. If different design criteria are required by the purchaser, they should be specified by the purchaser, stated in the contract documents, and accounted for in the design of the pipe.

III. Use of This Standard. It is the responsibility of the user of an AWWA standard to determine that the products described in that standard are suitable for use in the particular application being considered.

III.A. Purchaser Options and Alternatives. For LCP designs not included in the standard design tables and for all ECP designs, the design procedures specified in the standard must be implemented. For this purpose, the following information is to be provided by the purchaser:

1. Inside diameter of pipe (in. [mm]).
2. Fluid unit weight (lb/ft³ [kg/m³]) if a fluid other than fresh water is required.
3. Height of earth cover over the pipe (ft [m]) or external dead load (lb/ft [kg/m]).

4. External surcharge load (lb/ft [kg/m]).
5. External transient load (lb/ft [kg/m]) if loading other than AASHTO* HS20 loading is required.
6. Internal working pressure (psi [kPa]).
7. Internal transient pressure (psi [kPa]).
8. Internal field-test pressure (psi [kPa]).
9. Installation requirements.
10. Time period of exposure to outdoor environment (days) if more than 270 days.
11. Relative humidity of the outdoor environment.
12. Time exposure of pipe to burial environment before water filling (days) if more than 90 days.

III.A.1 *Information to Be Provided by the Pipe Manufacturer.* In addition to the information listed above (Sec. III.A), the following information is to be provided by the pipe manufacturer:

1. Outside diameter of the steel cylinder (in. [mm]).
2. Thickness of the steel cylinder (in. [mm]).
3. Diameter of prestressing wire (in. [mm]).
4. Class of prestressing wire (II or III).
5. Number of layers of prestressing wire (one, two, or three).
6. Coating thickness over the prestressing wire (in. [mm]).
7. Coating thickness between layers of prestressing wire (in. [mm]).
8. Concrete 28-day compressive strength (psi [MPa]).
9. Concrete modulus of elasticity multiplier, if less than 0.9.
10. Concrete creep factor multiplier, if greater than 1.1.
11. Concrete shrinkage strain multiplier, if greater than 1.1.
12. Prestressing wire intrinsic relaxation multiplier, if greater than 1.1.

III.B. *Modification to Standard.* Any modifications to the provisions, definitions, or terminology in this standard must be provided by the purchaser.

IV. Major Revisions. The major revisions made to the standard in this edition include the following:

* American Association of State Highway and Transportation Officials, 444 North Capitol Street NW, Suite 249, Washington, DC 20001.

1. In Sec. 2.3.1.1, the unit weights for concrete and mortar have been changed from 150 and 144 lb/ft³ (2,403 and 2,307 kg/m³) to 145 and 140 lb/ft³ (2,323 and 2,243 kg/m³), respectively, to match the unit weights in Sec. 5.3.4 and 5.4.3.

2. In Sec. 2.3.1.3, an alternate criterion has been added for surcharge load computed in accordance with recognized and documented analytical procedures based on soil–pipe interaction.

3. In Sec. 5.5.1, the design yield strength of the steel cylinder in tension has been changed from 33,000 psi to 36,000 psi (227 to 248 MPa).

4. Numerous editorial improvements and reference updates have been made throughout the standard.

V. Comments. If you have any comments or questions about this standard, please call AWWA Engineering and Technical Services at 303.794.7711, FAX at 303.795.7603; write to the department at 6666 West Quincy Avenue, Denver, CO 80235-3098; or email at standards@awwa.org.



**American Water Works
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(Revision of ANSI/AWWA C304-07)
Reaffirmed without revision 2019

AWWA Standard

Design of Prestressed Concrete Cylinder Pipe

SECTION 1: GENERAL

Sec. 1.1 Scope

This standard defines the methods to be used in the structural design of buried prestressed concrete cylinder pipe (PCCP) under internal pressure. These methods are provided for the design of pipe subjected to the effects of working, transient, and field-test load and internal pressure combinations.

The design procedures of this standard are applicable to lined-cylinder pipe (LCP) having inside diameters of 16 in. through 60 in. (410 mm through 1,520 mm) and to embedded-cylinder pipe (ECP) having inside diameters of 24 in. (610 mm) and larger.

The design for longitudinal hydrostatic thrust restraint of prestressed concrete cylinder pipe is not addressed in this standard. See AWWA Manual M9, *Concrete Pressure Pipe*, for information on this topic.

Sec. 1.2 References

Standard requirements for the manufacture of PCCP are contained in ANSI*/AWWA C301, Prestressed Concrete Pressure Pipe, Steel-Cylinder Type. Procedures

* American National Standards Institute, 25 West 43rd Street, Fourth Floor, New York, NY 10036.

for installation of the pipe are described in AWWA Manual M9, *Concrete Pressure Pipe*.

This standard references the following documents. In their current editions, they form a part of this standard to the extent specified in this standard. In any case of conflict, the requirements of this standard shall prevail.

AASHTO*—*Standard Specifications for Highway Bridges*, 17th Edition.

ACI† 209R—*Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures*.

American Concrete Pipe Association (ACPA)‡—*Concrete Pipe Design Manual*.

American Railway Engineering and Maintenance-of-Way Association (AREMA)§—*Manual for Railway Engineering*.

ANSI/AWWA C301—Prestressed Concrete Pressure Pipe, Steel-Cylinder Type.

ASTM¶ A648—Standard Specification for Steel Wire, Hard Drawn for Prestressing Concrete Pipe.

ASTM C33—Standard Specification for Concrete Aggregates.

ASTM C39—Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

ASTM C192/C192M—Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory.

ASTM C469—Standard Test for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression.

ASTM C512—Standard Test Method for Creep of Concrete in Compression.

AWWA Manual M9—*Concrete Pressure Pipe*.

FAA** AC150/5320-6C—Airport Pavement Design and Evaluation.

FAA AC150/5325-5C—Aircraft Data.

Sec. 1.3 Applications

PCCP is used principally in the transmission and distribution of water in municipal, industrial, and irrigation systems. It is also used in plant piping systems,

* American Association of State Highway and Transportation Officials, 444 North Capitol Street NW, Suite 249, Washington, DC 20001.

† American Concrete Institute, 38800 Country Club Drive, Farmington Hills, MI 48331.

‡ American Concrete Pipe Association, 1303 West Walnut Hill Lane, Suite 305, Irving, TX 75038.

§ American Railway Engineering and Maintenance-of-Way Association, 10003 Derekwood Lane, Suite 210, Lanham, MD 20706.

¶ ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

** Federal Aviation Administration, 800 Independence Avenue SW, Washington, DC 20591.

seawater cooling systems, sewer force mains, and gravity sewers. Other applications include inverted siphons, liners for pressure tunnels, and culverts with high earth covers.

Sec. 1.4 Pipe Structure

Two types of PCCP are produced: LCP and ECP. The cross sections and elements of both types of pipe are shown in Figure 1.

PCCP is made up of the following components:

1. A high-strength concrete core acts as the principal structural component of the pipe and provides a smooth inner surface for high fluid flow. The core includes a steel cylinder that functions as a watertight membrane, provides longitudinal tensile strength, and increases circumferential and beam strength. In ECP,

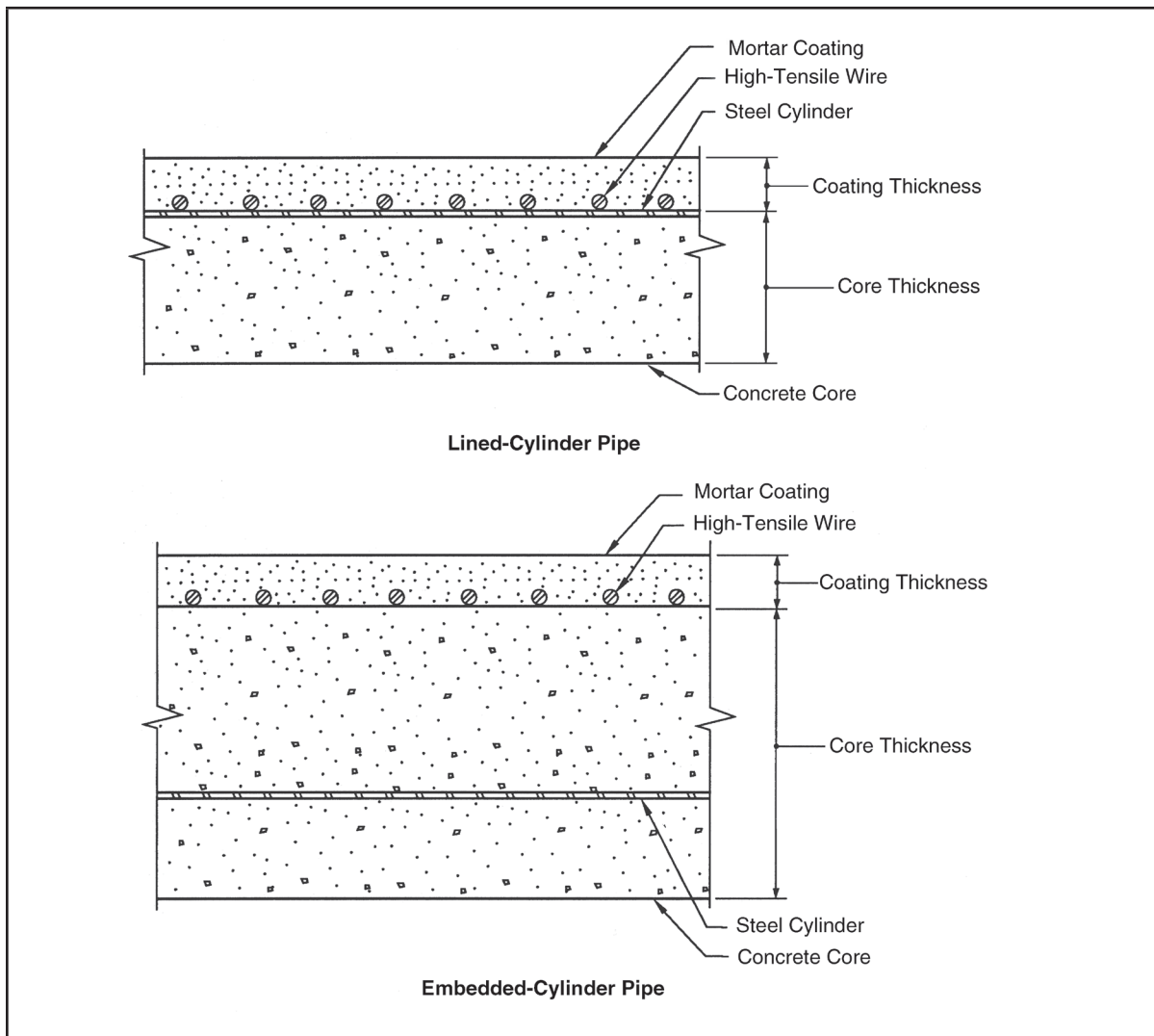


Figure 1 Schematic pipe-wall cross sections for LCP and ECP

the steel cylinder is contained within the core; in LCP, the steel cylinder forms the outer element of the core. Attached to the steel cylinder are steel bell-and-spigot joint rings that, together with an elastomeric O-ring, provide a watertight and self-centering joint between sections of pipe. Concrete for ECP is vertically cast within steel molds. LCP concrete is centrifugally cast or placed within the steel cylinder by radial compaction.

2. High-tensile steel wire, helically wrapped around the core under controlled tension, produces uniform compressive prestress in the core that offsets tensile stresses from internal pressure and external loads. PCCP can be designed to provide the optimum amount of prestress needed for the required operating conditions.

3. A dense cement–mortar coating encases and protects the wire-wrapped prestressed core from physical damage and external corrosion.

Sec. 1.5 Tolerances

The design procedures of this standard are consistent with the manufacturing tolerances given in ANSI/AWWA C301.

Sec. 1.6 Definitions

1. *Limit state:* A condition that bounds structural usefulness. The following three types of limit states are considered in the design of PCCP:

- a. Serviceability limit states, which ensure performance under service loads.
- b. Elastic limit states, which define the onset of material nonlinearity.
- c. Strength limit states, which provide appropriate safety factors against structural failure modes.

2. *Limit-states design:* The limit-states design method requires definitions of all limit states that are relevant to the performance of the pipe so that the probability of exceeding a limit state is acceptably low.

3. *Purchaser:* The person, company, or organization that purchases any materials or work to be performed.

Sec. 1.7 Metric (SI) Equivalents

The following provides conversion factors for US customary units to metric (SI) units. Values of constants and variables are given in both US customary and SI units throughout the standard. In those instances where direct conversion of units is not possible, equations applicable to both US and SI systems of units are given in this standard.

To convert from	to	Multiply by
Area		
square inches (in. ²)	square meters (m ²)	0.000645
Bending Moment		
poundforce inches (lbf-in.)	newton meters (N·m)	0.112985
Force		
pounds-force (lbf)	newtons (N)	4.448222
Length		
feet (ft)	meters (m)	0.304800
inches (in.)	meters (m)	0.025400
Weight per Unit Volume		
pounds per cubic foot (lb/ft ³)	kilograms per cubic meter (kg/m ³)	16.018
Pressure or Stress		
pounds per square inch (psi)	kilopascals (kPa)	6.895
Steel Area per Unit Length of Pipe		
square inches per foot (in. ² /ft)	square millimeters per meter (mm ² /m)	2116.667
Temperature		
degrees Fahrenheit (°F)	degrees Celsius (°C)	$T_C = (T_F - 32)/1.8$
Volume		
cubic yards (yd ³)	cubic meters (m ³)	0.764555

SECTION 2: LOADS AND INTERNAL PRESSURES

Sec. 2.1 Notation

D_i = inside diameter of pipe (in. [mm])

H = height of earth cover over pipe (ft [m])

I_f = impact factor

P_{ft} = internal field-test pressure (psi [kPa])

P_g = internal pressure established by the hydraulic gradient (psi [kPa])

P_s = internal pressure established by the static head (psi [kPa])

P_t = internal transient pressure (psi [kPa])

P_w = internal working pressure (psi [kPa]) = $\max(P_g, P_s)$

W_e = external dead load (lbf/ft [N/m])

W_f = weight of fluid (lbf/ft [N/m])

W_p = weight of pipe (lbf/ft [N/m])

W_s = surcharge load (lb/ft [N/m])

W_t = transient load (lb/ft [N/m])

γ_c = unit weight of concrete (lb/ft³ [kg/m³])

γ_m = unit weight of mortar (lb/ft³ [kg/m³])

γ_s = unit weight of steel (lb/ft³ [kg/m³])

Sec. 2.2 Design Loads and Internal Pressures

To purchase pipe manufactured according to ANSI/AWWA C301, the purchaser must specify the magnitudes of design loads and internal pressures and the distributions of external loads on the pipe. The types of loads and internal pressures described in Sec. 2.3 and 2.4 are those normally required for the design of buried pressure pipe. The references given for determining various external loads and their distributions are guidelines that define acceptable practice. The purchaser may need to specify additional loads for special conditions not covered by this standard.

Sec. 2.3 Loads

2.3.1 *Working loads.* Pipe shall be designed to include the following working loads of long duration.

2.3.1.1 Pipe weight, W_p , computed using nominal pipe dimensions and the following material unit weights:

$$\gamma_c = 145 \text{ lb/ft}^3 (2,323 \text{ kg/m}^3)$$

$$\gamma_m = 140 \text{ lb/ft}^3 (2,243 \text{ kg/m}^3)$$

$$\gamma_s = 489 \text{ lb/ft}^3 (7,833 \text{ kg/m}^3)$$

2.3.1.2 Fluid weight, W_f , computed using 62.4 lb/ft³ (1,000 kg/m³) as the unit weight of fresh water. If fluids other than fresh water are to be transported by the pipe, then the actual unit weight of those fluids shall be used.

2.3.1.3 External dead load, W_e , computed as the sum of earth load and surcharge load, if any.

Earth load is computed in accordance with AWWA Manual M9; ACPA's *Concrete Pipe Design Manual*; AASHTO's *Standard Specifications for Highway Bridges: 2002*, 17th edition, division I, section 16.4; or recognized and documented analytical procedures acceptable to the purchaser that are based on soil-pipe interaction.

Surcharge load, resulting from the dead load of structures or other surface loads that are not transient loads as defined in Sec. 2.3.2, is computed in accordance with ACPA's *Concrete Pipe Design Manual* or recognized and documented analytical procedures acceptable to the purchaser.

2.3.2 *Transient loads.* Transient load, W_t , for which the pipe shall be designed, includes the following vertical surface loads of short duration, whenever applicable.

2.3.2.1 Highway live load, if specified by the purchaser, shall be computed in accordance with, AASHTO's *Standard Specifications for Highway Bridges: 2002*, 17th edition; AWWA Manual M9; and ACPA's *Concrete Pipe Design Manual*. HS20 loading shall be used unless other loading is specified by the purchaser.

2.3.2.2 Railroad live load, if specified by the purchaser, shall be computed in accordance with AREMA's *Manual for Railway Engineering* and ACPA's *Concrete Pipe Design Manual*. Cooper E-72 loading shall be used unless other loading is specified by the purchaser.

2.3.2.3 Aircraft live load, if specified by the purchaser, shall be computed using appropriate aircraft wheel loads (see FAA AC150/5325-5C, Aircraft Data), in accordance with FAA AC150/5320-6C, Airport Pavement Design and Evaluation, and ACPA's *Concrete Pipe Design Manual*.

2.3.2.4 Construction live load, if specified by the purchaser, shall be computed using the specified load and earth cover in accordance with ACPA's *Concrete Pipe Design Manual* procedure for highway live load.

2.3.3 *Impact factor.* Computation of W_t shall include the application of an appropriate impact factor, I_f , in accordance with the applicable live load standard or ACPA's *Concrete Pipe Design Manual*.

Sec. 2.4 Internal Pressures

2.4.1 *Internal working pressure.* The internal working pressure, P_w , for which the pipe shall be designed is:

$$P_w = \max(P_g, P_s) \quad (\text{Eq 2-1})$$

2.4.2 *Internal transient pressure.* The internal transient pressure, P_t , for which the pipe shall be designed is the internal pressure, in excess of the internal working pressure, P_w , caused by rapid changes in pipeline flow velocity. The hydraulic design of the pipeline should include an analysis of transient effects. In the absence of a design transient pressure specified by the purchaser, the value of P_t for which the pipe shall be designed is:

$$P_t = \max(0.4P_w, 40 \text{ psi [276 kPa]}) \quad (\text{Eq 2-2})$$

2.4.3 *Internal field-test pressure.* The internal field-test pressure, P_{ft} , is the test pressure to be applied to the pipe after its installation. In the absence of a

field-test pressure specified by the purchaser, the value of P_{ft} for which the pipe shall be designed is:

$$P_{ft} = 1.2P_w \quad (\text{Eq 2-3})$$

SECTION 3: LOAD AND INTERNAL-PRESSURE COMBINATIONS

Sec. 3.1 Notation

- f_{cr} = field prestress in core concrete (psi [kPa])
- FT1, FT2 = design-factored working-load and field-test pressure combinations
- FW1 = design-factored working-load combination
- FWT1–FWT6 = design-factored working plus transient load and internal-pressure combinations
- P_{ft} = internal field-test pressure (psi [kPa])
- P_g = internal pressure caused by the hydraulic gradient (psi [kPa])
- P_s = internal pressure caused by the static head (psi [kPa])
- P_t = internal transient pressure (psi [kPa])
- P_w = internal working pressure (psi [kPa]) = $\max(P_g, P_s)$
- W1, W2 = design working-load and internal-pressure combinations
- W_e = external dead load (lbf/ft [N/m])
- W_f = weight of fluid (lbf/ft [N/m])
- W_p = weight of pipe (lbf/ft [N/m])
- W_t = transient load (lbf/ft [N/m])
- WT1–WT3 = design working plus transient load and internal-pressure combinations
- β_1 = factor equal to 1.1 for ECP and 1.2 for LCP
- β_2 = factor equal to 1.3 for ECP and 1.4 for LCP

Sec. 3.2 Load Factors for Limit-States Design*

The factored load combinations given in this section are based on minimum recommended load factors for use with the limit-states design procedures described in Section 8.

* For commentary see appendix A, Sec. A.2.

Sec. 3.3 Minimum Combined Design Loads and Pressures

1. The minimum combined design pressure and load shall be $P_w = 40$ psi (276 kPa) in combination with W_e equivalent to 6 ft (1.83 m) of earth cover based on trench loading at transition width, and unit earth weight of 120 lb/ft³ (1,922 kg/m³) with 45° Olander bedding for earth load and fluid weight and 15° Olander bedding for pipe weight. $P_t = 0$, and $W_t = 0$.

2. The maximum calculated tensile stress in the pipe core shall not exceed f_{cr} when the pipe weight alone is supported on a line bearing.

Sec. 3.4 Working Loads and Internal Pressures

Pipe shall be designed for all of the following combinations of working loads and internal pressures:

$$W1: W_e + W_p + W_f + P_w \quad (\text{Eq 3-1})$$

$$W2: W_e + W_p + W_f \quad (\text{Eq 3-2})$$

$$FW1: 1.25W_e + W_p + W_f \quad (\text{Eq 3-3})$$

Sec. 3.5 Working Plus Transient Loads and Internal Pressures

3.5.1 *Load and pressure combinations.** Pipe shall be designed for all of the following combinations of working plus transient loads and internal pressures:

$$WT1: W_e + W_p + W_f + P_w + P_t \quad (\text{Eq 3-4})$$

$$WT2: W_e + W_p + W_f + W_t + P_w \quad (\text{Eq 3-5})$$

$$WT3: W_e + W_p + W_f + W_t \quad (\text{Eq 3-6})$$

$$FWT1: \beta_1 (W_e + W_p + W_f + P_w + P_t) \quad (\text{Eq 3-7})$$

$$FWT2: \beta_1 (W_e + W_p + W_f + W_t + P_w) \quad (\text{Eq 3-8})$$

Where:

$$\beta_1 = 1.1 \text{ for ECP and } 1.2 \text{ for LCP}$$

3.5.2 *Factored load and pressure combinations.†* Pipe shall be designed for the following factored combinations of working plus transient loads and internal pressures:

$$FWT3: \beta_2 (W_e + W_p + W_f + P_w + P_t) \quad (\text{Eq 3-9})$$

$$FWT4: \beta_2 (W_e + W_p + W_f + W_t + P_w) \quad (\text{Eq 3-10})$$

$$FWT5: 1.6(W_e + W_p + W_f) + 2.0W_t \quad (\text{Eq 3-11})$$

$$FWT6: 1.6P_w + 2.0P_t \quad (\text{Eq 3-12})$$

* For commentary see appendix A, Sec. A.3.

† For commentary see appendix A, Sec. A.4.

Where:

$$\beta_2 = 1.3 \text{ for ECP and } 1.4 \text{ for LCP}$$

Sec. 3.6 Working Loads and Internal Field-Test Pressures*

Pipe shall be designed for the following combinations of working loads and internal field-test pressures:

$$\text{FT1: } 1.1(W_e + W_p + W_f + P_{ft}) \quad (\text{Eq 3-13})$$

$$\text{FT2: } 1.1\beta_1(W_e + W_p + W_f + P_{ft}) \quad (\text{Eq 3-14})$$

Where:

$$\beta_1 = 1.1 \text{ for ECP and } 1.2 \text{ for LCP}$$

Sec. 3.7 Load and Pressure Factors

The load and pressure factors for the various loading conditions are summarized in Table 1 for ECP and in Table 2 for LCP.

Table 1 Load and pressure factors for embedded-cylinder pipe

Loading Conditions	Load and Pressures						
	W_e	W_p	W_f	W_t	P_w	P_t	P_{ft}
Working Load and Pressure Combinations							
W1	1.0	1.0	1.0	—	1.0	—	—
W2	1.0	1.0	1.0	—	—	—	—
FW1	1.25	1.0	1.0	—	—	—	—
Working Plus Transient Load and Pressure Combinations							
WT1	1.0	1.0	1.0	—	1.0	1.0	—
WT2	1.0	1.0	1.0	1.0	1.0	—	—
WT3	1.0	1.0	1.0	1.0	—	—	—
FWT1	1.1	1.1	1.1	—	1.1	1.1	—
FWT2	1.1	1.1	1.1	1.1	1.1	—	—
FWT3	1.3	1.3	1.3	—	1.3	1.3	—
FWT4	1.3	1.3	1.3	1.3	1.3	—	—
FWT5	1.6	1.6	1.6	2.0	—	—	—
FWT6	—	—	—	—	1.6	2.0	—
Field-Test Condition							
FT1	1.1	1.1	1.1	—	—	—	1.1
FT2	1.21	1.21	1.21	—	—	—	1.21

* For commentary see appendix A, Sec. A.5.

Table 2 Load and pressure factors for lined-cylinder pipe

Loading Conditions	Load and Pressures						
	W_e	W_p	W_f	W_t	P_w	P_t	P_{ft}
Working Load and Pressure Combinations							
W1	1.0	1.0	1.0	—	1.0	—	—
W2	1.0	1.0	1.0	—	—	—	—
Working Plus Transient Load and Pressure Combinations							
WT1	1.0	1.0	1.0	—	1.0	1.0	—
WT2	1.0	1.0	1.0	1.0	1.0	—	—
WT3	1.0	1.0	1.0	1.0	—	—	—
FWT1	1.2	1.2	1.2	—	1.2	1.2	—
FWT2	1.2	1.2	1.2	1.2	1.2	—	—
FWT3	1.4	1.4	1.4	—	1.4	1.4	—
FWT4	1.4	1.4	1.4	1.4	1.4	—	—
FWT5	1.6	1.6	1.6	2.0	—	—	—
FWT6	—	—	—	—	1.6	2.0	—
Field-Test Condition							
FT1	1.1	1.1	1.1	—	—	—	1.1
FT2	1.32	1.32	1.32	—	—	—	1.32

SECTION 4: MOMENTS AND THRUSTS

Sec. 4.1 Notation

C_{m1e} , C_{m1p} , C_{m1f} = moment coefficients at invert resulting from the distribution of external loads, W_e or W_t , and pipe and fluid weights, W_p and W_f

C_{m2e} , C_{m2p} , C_{m2f} = moment coefficients at springline resulting from the distribution of external loads, W_e or W_t , and pipe and fluid weights, W_p and W_f

C_{n1e} , C_{n1p} , C_{n1f} = thrust coefficients at invert resulting from the distribution of external loads, W_e or W_t , and pipe and fluid weights, W_p and W_f

C_{n2e} , C_{n2p} , C_{n2f} = thrust coefficients at springline resulting from the distribution of external loads, W_e or W_t , and pipe and fluid weights, W_p and W_f

D_i = inside diameter of pipe (in. [mm])

D_y = outside diameter of steel cylinder (in. [mm])

- h_c = core thickness, including thickness of cylinder (in. [mm])
 h_m = coating thickness, including wire diameter (in. [mm])
 M_1 = total moment at invert (lbf-in./ft [N-m/m])
 M_2 = total moment at springline (lbf-in./ft [N-m/m])
 M_{2r} = redistributed moment at springline (lbf-in./ft [N-m/m])
 M_{1cap} = moment capacity at invert and crown (lbf-in./ft [N-m/m])
 N_1 = total thrust at invert (lbf/ft [N/m])
 N_2 = total thrust at springline (lbf/ft [N/m])
 N_o = thrust resulting from final prestress (lbf/ft [N/m])
 P = internal pressure (psi [kPa])
 P_o = decompression pressure that relieves final prestress in the core concrete (psi [kPa])
 $\bar{R}$ = radius to the centroid of the coated pipe wall (in. [mm])
 W_e = external dead load (lbf/ft [N/m])
 W_f = fluid weight (lbf/ft [N/m])
 W_p = weight of pipe (lbf/ft [N/m])
 W_t = transient load (lbf/ft [N/m])

Sec. 4.2 Distribution of Loads

The total working and transient loads on the pipe shall be determined using the provisions of Section 2. The earth-pressure distribution on the pipe and the moments and thrusts in the wall resulting from the working and transient loads shall be determined from recognized and accepted theories, taking into account the characteristics of installation, such as those given by Olander (1950) and Paris (1921) (see appendix B). The bedding angle for Olander and Paris distributions shall be selected on the basis of design pipe–soil installation. Unless provisions are made to support the pipe weight over a wider width, the bedding angle for pipe weight shall be 15° for installation on soil beddings.

Sign conventions for moments and thrusts in the references cited above may differ. The sign conventions for moments and thrusts in this standard are

1. A thrust in the pipe wall is positive when creating tension in the pipe wall and negative when creating compression in the pipe wall.
2. In the vicinity of the crown and invert, a moment is positive when creating tension at the inside surface of the pipe and negative when creating compression at the inside surface of the pipe.
3. In the vicinity of the springline, a moment is positive when creating tension at the outside surface of the pipe and negative when creating compression at the outside surface of the pipe.

Sec. 4.3 Moments and Thrusts

4.3.1 *Prestress thrust.* The thrust at invert, crown, and springline resulting from prestressing is

$$N_o = 6D_y P_o \quad (\text{Eq 4-1})$$

Where:

P_o = the decompression pressure that relieves the final prestress in the core, as defined in Sec. 6.3.3. D_y is in inches, and P_o is in psi. The metric equivalent of Eq 4-1, with D_y in mm and P_o in kPa, is

$$N_o = \frac{D_y P_o}{2}$$

4.3.2 *Moments and thrusts from combined loads.** The moments and thrusts resulting from pressure, external loads (earth, surcharge, transient, and construction loads), and weights of pipe and fluid, for a pipe with uniform wall, are

$$M_1 = \bar{R}[C_{m1e}(W_e + W_t) + C_{m1p}W_p + C_{m1f}W_f] \quad (\text{Eq 4-2})$$

$$M_2 = \bar{R}[C_{m2e}(W_e + W_t) + C_{m2p}W_p + C_{m2f}W_f] \quad (\text{Eq 4-3})$$

$$N_1 = 6D_y P - [C_{n1e}(W_e + W_t) + C_{n1p}W_p + C_{n1f}W_f] \quad (\text{Eq 4-4})$$

$$N_2 = 6D_y P - [C_{n2e}(W_e + W_t) + C_{n2p}W_p + C_{n2f}W_f] \quad (\text{Eq 4-5})$$

Where:

$$\bar{R} = \frac{D_i + h_c + h_m}{2} \quad (\text{Eq 4-6})$$

When D_y is in mm and P is in kPa, substitute $\frac{1}{2}D_y$ for $6D_y$ in Eq 4-4 and 4-5. The moment and thrust coefficients are obtained from the assumed distribution of earth pressure selected for the design installation.

4.3.3 *Moment redistribution.†* When the moment, M_1 , given by Eq 4-2 is greater than the moment capacity at the invert, M_{1cap} , the moments at the invert and springline, M_1 and M_2 , obtained using Eq 4-2 and 4-3, shall be redistributed as described in this section. M_{1cap} for ECP is the M_1 -moment limit at the invert corresponding to the steel-cylinder stress reaching a limiting value and is computed according to the procedure in Sec. 7.4.2 and 8.9.1. M_{1cap} for LCP is the M_1 -moment limit at the invert corresponding to the coating strain reaching the compressive strain limit after cracking of the core and is computed according to

* For commentary see appendix A, Sec. A.6.

† For commentary see Appendix A, Sec. A.7.

the procedure in Sec. 8.9.4. For loads exceeding the limiting load that produces M_{1cap} at the invert, the redistributed moment at the springline M_{2r} is

$$M_{2r} = M_1 + M_2 - M_{1cap} \quad (\text{Eq 4-7})$$

Where M_1 and M_2 are given by Eq 4-2 and 4-3.

SECTION 5: DESIGN MATERIAL PROPERTIES

Sec. 5.1 Notation

- C_E = concrete modulus of elasticity multiplier
- C_s = concrete shrinkage strain multiplier
- C_ϕ = concrete creep-factor multiplier
- E_c = design modulus of elasticity of core concrete (psi [MPa])
- E_{ct} = average modulus of elasticity of test concrete (psi [MPa])
- E_m = design modulus of elasticity of coating mortar (psi [MPa])
- E_s = design modulus of elasticity of prestressing wire (psi [MPa])
- E_y = design modulus of elasticity of steel cylinder (psi [MPa])
- f'_c = design 28-day compressive strength of core concrete (psi [MPa])
- f'_{ci} = core concrete compressive strength at wrapping (psi [MPa])
- f'_{ct} = design compressive strength of test concrete (psi [MPa])
- f'_m = design 28-day compressive strength of coating mortar (psi [MPa])
- f'_{tm} = design 28-day tensile strength of coating mortar (psi [MPa])
- f'_t = design tensile strength of core concrete (psi [MPa])
- f_s = tensile stress in prestressing wire (psi [MPa])
- f_{sg} = gross wrapping tensile stress in wire (psi [MPa])
- f_{su} = specified minimum tensile strength of prestressing wire (psi [MPa])
- f_{sy} = tensile yield strength of prestressing wire (psi [MPa])
- f_{yy} = design tensile or compressive yield strength of steel cylinder (psi [MPa])
- f_{yy}^* = design tensile strength of steel cylinder at pipe burst (psi [MPa])
- $s(18,250)$ = extrapolated shrinkage strain of concrete test specimens at 50 years (18,250 days)
- $s_t(n)$ = shrinkage strain of concrete test specimens on n -th day after loading
- ϵ_s = strain in prestressing wire
- γ_c = unit weight of concrete (lb/ft³ [kg/m³])
- γ_m = unit weight of mortar (lb/ft³ [kg/m³])
- $\phi(18,250)$ = creep factor at 50 years (18,250 days)

Sec. 5.2 Materials and Manufacturing Standard

The concrete core, mortar coating, steel cylinder, and prestressing wire shall conform to the requirements of ANSI/AWWA C301.

Sec. 5.3 Properties of Core Concrete

The core concrete may be placed by the centrifugal-casting method, by the vertical-casting method, or by the radial-compaction method. In this standard, the concrete placed by the centrifugal method is referred to as *spun concrete* and that placed by the vertical-casting method is referred to as *cast concrete*. Concrete placed by radial compaction, which has been shown to have strength, shrinkage, and creep properties equivalent to spun concrete, is also considered as spun concrete in this standard.

5.3.1 *Compressive strength of concrete.* The minimum design compressive strength of the core concrete, based on 28-day tests of concrete cylinders in accordance with ANSI/AWWA C301, shall be as follows:

Cast concrete $f'_c = 4,500$ psi (31.0 MPa)

Spun concrete $f'_c = 6,000$ psi (41.4 MPa)

5.3.2 *Minimum compressive strength of concrete at wrapping.* The minimum compressive strength of the core concrete, based on tests of concrete cylinders in accordance with ANSI/AWWA C301, at the time of wrapping shall be as follows:

Cast concrete $f'_{ci} = 3,000$ psi (20.7 MPa)

Spun concrete $f'_{ci} = 4,000$ psi (27.6 MPa)

but not less than 1.8 times the initial prestress in the core (that is, the initial prestress in the core shall not exceed $0.55f'_{ci}$).

5.3.3 *Tensile strength of concrete.** The design tensile strength of the core concrete is

$$f'_t = 7\sqrt{f'_c} \quad (\text{Eq 5-1})$$

Where:

f'_c = design 28-day compressive strength of core concrete in psi

$$f'_t = 0.58\sqrt{f'_c}$$

Where:

f'_c = design 28-day compressive strength of core concrete in MPa

* For commentary see appendix A, Sec. A.8.

5.3.4 *Modulus of elasticity of concrete.** The design modulus of elasticity of the core concrete is

$$E_c = 158\gamma_c^{1.51}(f'_c)^{0.3} \quad (\text{Eq 5-2})$$

Where:

$$\gamma_c = 145 \text{ lb/ft}^3$$

f'_c = design 28-day compressive strength of concrete in psi

$$E_c = 0.074\gamma_c^{1.51}(f'_c)^{0.3}$$

Where:

$$\gamma_c = 2,323 \text{ kg/m}^3$$

f'_c = design 28-day compressive strength of concrete in MPa

Each factory where PCCP is to be manufactured shall perform a quality-assurance test to determine the modulus of elasticity of the concrete mix with the aggregates and cement to be used in the pipe manufacture. If the measured modulus of elasticity is less than the value computed from Eq 5-2, the design modulus of elasticity shall be modified for all pipe manufactured using these aggregates and cement.

The average modulus of elasticity of concrete produced at the factory shall be determined from tests of at least five molded cylindrical test specimens of concrete meeting the requirements of ANSI/AWWA C301. The test specimens shall be molded and cured in accordance with ASTM C192 and tested in accordance with ASTM C469 at an age of 28 days to determine their modulus of elasticity.

Five companion test specimens shall be molded and cured in accordance with ASTM C192 and tested in accordance with ASTM C39. The mean 28-day compressive strength $\bar{x}$ and the standard deviation s of the sample of five test specimens shall be computed. The design 28-day compressive strength of the test concrete shall be

$$f'_{ct} = \bar{x} - 0.84s \quad (\text{Eq 5-3})$$

For purposes of these tests, f'_{ct} shall range from 4,500 to 6,500 psi (31.0 to 44.8 MPa).

The modulus of elasticity multiplier is

$$C_E = \frac{E_{ct}}{158\gamma_c^{1.51}(f'_{ct})^{0.3}} \quad (\text{Eq 5-4})$$

* For commentary see appendix A, Sec. A.9.

Where:

E_{ct} (psi) = the average of the five or more modulus of elasticity test results
 $\gamma_c = 145 \text{ lb/ft}^3$

$$C_E = \frac{E_{ct}}{0.074\gamma_c^{1.51}(f'_{ct})^{0.3}}$$

Where:

E_{ct} (MPa) = the average of the five or more modulus of elasticity test results
 $\gamma_c = 2,323 \text{ kg/m}^3$

If C_E is less than 0.9 for all pipe manufactured using the aggregates and cement used in the test, the design modulus of elasticity shall be reduced by multiplying the result of Eq 5-2 by C_E , and the modular ratios given in Sections 6 and 8 shall be increased by dividing them by C_E .

The quality-assurance test to determine modulus of elasticity shall be made annually or whenever the sources of aggregate or cement are changed.

5.3.5 Stress–strain relationship of concrete.* The design stress–strain relationship of the core concrete is shown in Figure 2A.

5.3.6 Creep and shrinkage properties of concrete. Each factory that manufactures PCCP shall perform a quality-assurance test of concrete creep and shrinkage on a mix with the aggregates and cement to be used in the manufacture of pipe (without additives or admixtures). If either the measured concrete creep factor or shrinkage strain is more than the value computed in accordance with ACI 209R, the design creep factor and shrinkage strain shall be modified for all pipe manufactured using these aggregates and cement.

The creep and shrinkage-strain properties of concrete produced at the factory shall be determined from tests of at least one set of molded cylindrical test specimens of concrete meeting the requirements of ANSI/AWWA C301. The test specimens shall be molded in accordance with ASTM C192. Each set of test specimens shall include five specimens for creep tests, five specimens for shrinkage tests, five specimens for modulus-of-elasticity tests, and 10 specimens for compressive-strength tests. Each of the specimens shall be cured and stored in accordance with the requirements for “Standard Curing” in Sec. 6.1 of ASTM C512. Creep specimens shall be tested in accordance with ASTM C512. Compressive strength and modulus of elasticity shall be determined in accordance with ASTM C39 and ASTM C469, respectively.

* For commentary see appendix A, Sec. A.10.

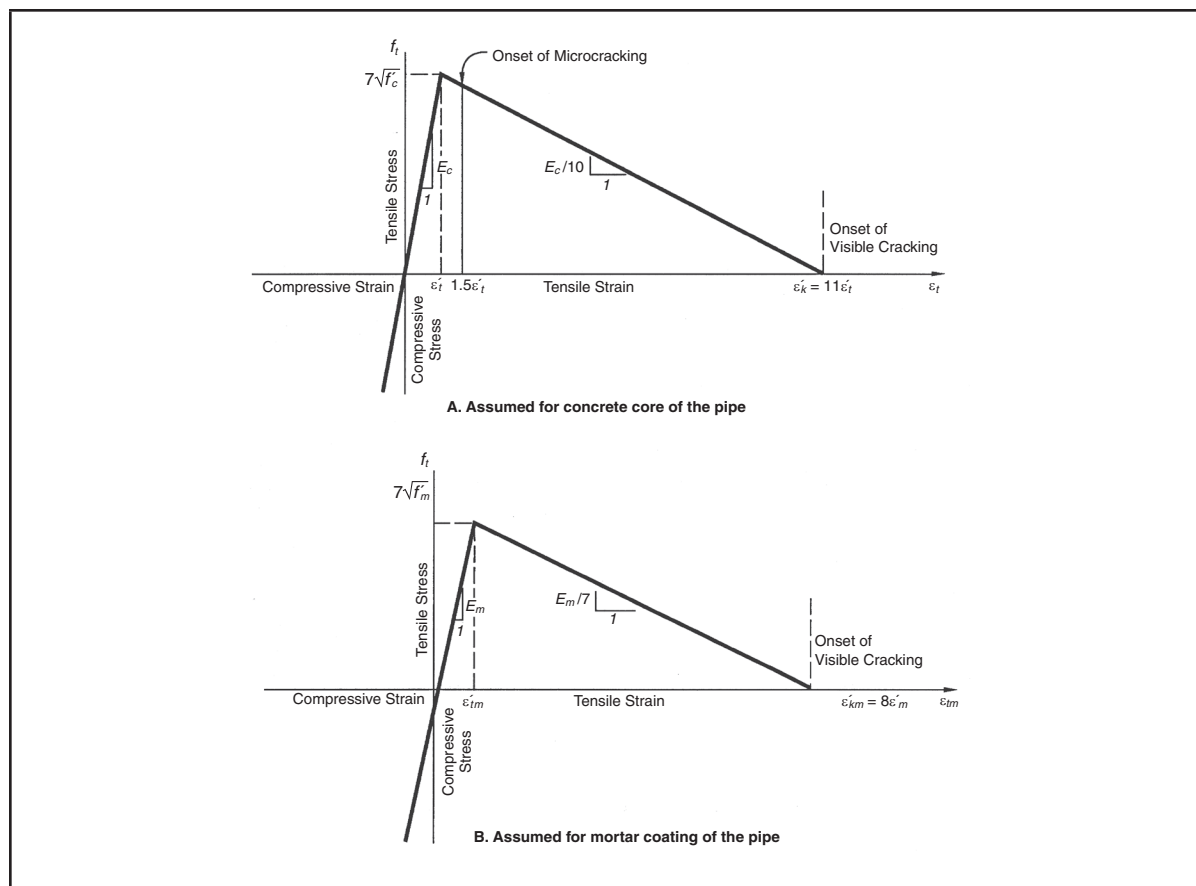


Figure 2 Stress-strain relationships for concrete and mortar in tension and compression

Immediately before loading the creep specimens, the compressive strength of concrete shall be determined by testing five of the strength specimens in accordance with ASTM C39.

Creep-test specimens shall be loaded at 7 days to a compressive stress level ranging from 30 to 40 percent of the compressive strength of the concrete at loading age.

Strain readings of loaded specimens shall be taken immediately before and after loading, 7 days after loading, and 28 days after loading. Shrinkage strains shall be measured at the same times as strain readings of loaded specimens. Additional strain readings may be taken at other times.

The 28-day compressive strength of concrete shall be determined by testing the remaining five strength specimens in accordance with ASTM C39 and averaging their results. The 28-day modulus of elasticity of concrete shall be determined by testing five test specimens in accordance with ASTM C469 and averaging their results.

In addition to the items required by ASTM C512 to be included in the report, the following items shall be reported:

1. Shrinkage strains at designated ages ($\mu\text{in./in.}$ [mm/mm]).
2. Compressive strength at 28 days of age (psi [MPa]).
3. Modulus of elasticity at 28 days of age (psi [MPa]).
4. Cement content of the concrete (lb/yd^3 [kg/m^3]).
5. Water–cement ratio.

The average of five specific creep strains plus the initial elastic strains measured up to 28 days after loading shall be extrapolated using the BP-KX model of drying creep (Bazant, Kim, and Panula [1991, 1992; see appendix B]) or the ACI 209R model of drying creep to compute the specific creep plus instantaneous strain at 50 years. A procedure for the extrapolation is discussed in Ojdrovic and Zarghamee (1996)(see appendix B). The resulting creep factor at 50 years is computed by dividing the specific creep strain at 50 years, $\phi(18,250)$, by the specific initial strain.

The concrete creep factor multiplier, C_ϕ , is the ratio of the creep factor at 50 years to the computed value of the creep factor using ACI 209R:

$$C_\phi = \frac{\phi(18,250)}{2.0}$$

If C_ϕ is greater than 1.1, for all pipe to be manufactured using the aggregates and cement used in the test, the design creep factor shall be increased by multiplying the creep factor ϕ given in Eq 6-16 by C_ϕ .

The average of five shrinkage strains measured at 28 days after loading of the creep specimens shall be extrapolated using the BP-KX model of shrinkage (Bazant, Kim, and Panula [1991, 1992; see appendix B]) or the ACI 209R model of shrinkage to compute the shrinkage strain at 50 years, $s(18,250)$. A procedure for the extrapolation is discussed in Ojdrovic and Zarghamee (1996) (see appendix B). The concrete shrinkage strain multiplier, C_s , is the ratio of the shrinkage strain at 50 years to the computed value of the shrinkage strain using ACI 209R:

$$C_s = \frac{s(18,250)}{700}$$

If C_s is greater than 1.1, for all pipe to be manufactured using the aggregates and cement used in the test, the design shrinkage strain shall be increased by multiplying the shrinkage strain s given in Eq 6-17 by C_s .

Creep and shrinkage measurements shall be made whenever the sources of aggregate or cement are changed.

Sec. 5.4 Properties of Coating Mortar

The mortar coating is a cement-rich mixture of sand and cement that is applied as a dense and durable coating with a minimum thickness of 0.75 in. (19 mm) over the outer layer of prestressing wire.

5.4.1 *Compressive strength of mortar.* The design compressive strength of the coating mortar is $f'_m = 5,500$ psi (37.9 MPa).

5.4.2 *Tensile strength of mortar.** The design tensile strength of the coating mortar is

$$f'_{tm} = 7\sqrt{f'_m} \quad (\text{Eq 5-5})$$

Where:

f'_m = design 28-day compressive strength of coating mortar in psi

$$f'_{tm} = 0.58\sqrt{f'_m}$$

Where:

f'_m = design 28-day compressive strength of coating mortar in MPa

5.4.3 *Modulus of elasticity of mortar.†* The design modulus of elasticity of the coating mortar is

$$E_m = 158\gamma_m^{1.51}(f'_m)^{0.3} \quad (\text{Eq 5-6})$$

Where:

$$\gamma_m = 140 \text{ lb/ft}^3$$

$$f'_m = 5,500 \text{ psi}$$

$$E_m = 0.074\gamma_m^{1.51}(f'_m)^{0.3}$$

Where:

$$\gamma_m = 2.242 \text{ kg/m}^3$$

$$f'_m = 37.9 \text{ MPa}$$

5.4.4 *Stress–strain relationship of mortar.* The design stress–strain relationship of coating mortar is shown in Figure 2B.

Sec. 5.5 Properties of Steel Cylinder

The cylinder shall be fabricated from either hot-rolled or cold-rolled steel sheet conforming to the requirements of ANSI/AWWA C301. The minimum wall thickness of the steel cylinder shall be USS 16 gauge (1.52 mm).

* For commentary see appendix A, Sec. A.8.

† For commentary see Appendix A, Sec. A.9.

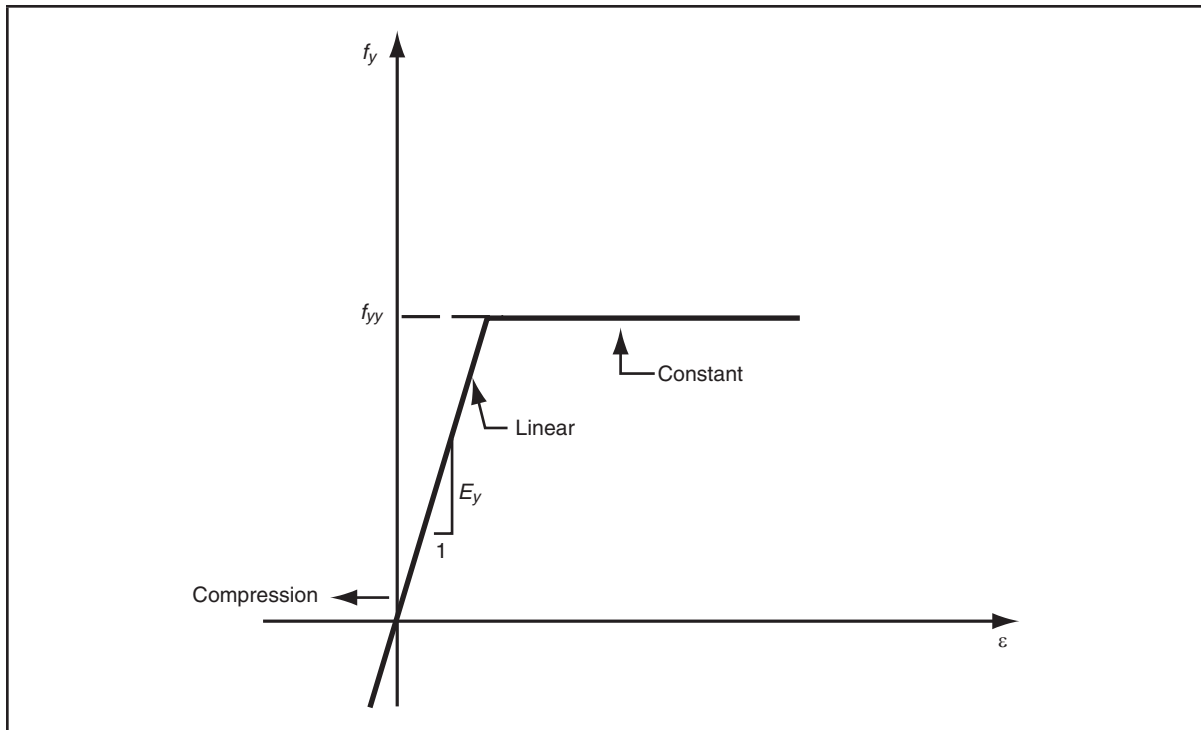


Figure 3 Stress–strain relationship for steel cylinder in tension and compression

5.5.1 *Yield strength of steel cylinder.* The design yield strength of the steel cylinder in tension shall be

$$f_{yy} = 36,000 \text{ psi (248 MPa)}$$

or the specified minimum yield strength, whichever is greater.

5.5.2 *Strength of steel cylinder at burst.** The usable design strength of the steel cylinder at burst for a pipe subjected to hydrostatic pressure shall be

$$f_{yy}^* = 45,000 \text{ psi (310 MPa)}$$

If the specified minimum yield strength of the cylinder steel is greater than 45,000 psi [310 MPa], the larger value may be used for f_{yy}^* .

5.5.3 *Modulus of elasticity of steel cylinder.* The design modulus of elasticity of the steel cylinder shall be

$$E_y = 30,000,000 \text{ psi (206,850 MPa)}$$

5.5.4 *Stress–strain relationship of steel cylinder.* The design stress–strain relationship for the steel cylinder is shown in Figure 3.

* For commentary see appendix A, Sec. A.11.

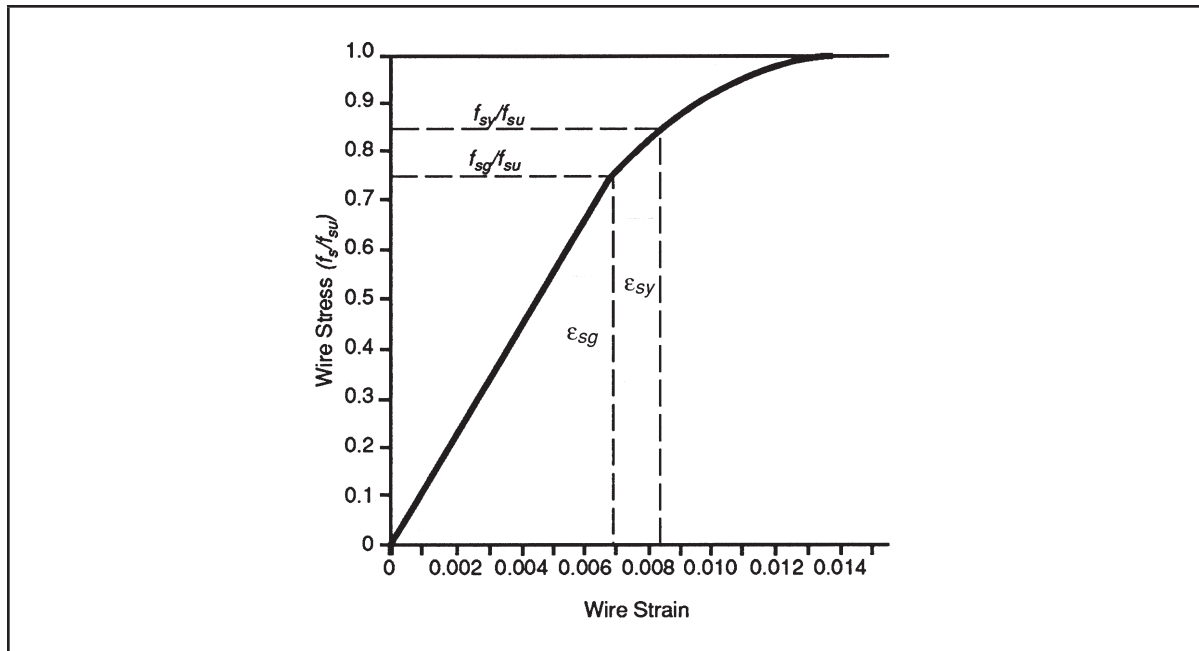


Figure 4 Stress-strain relationship for 6-gauge prestressing wire in tension after wrapping at f_{sg}

Sec. 5.6 Properties of Prestressing Wire

The prestressing wire shall be hard drawn steel wire conforming to ANSI/AWWA C301. The minimum diameter of wire shall be USS 6 gauge (4.88 mm) for all pipe sizes (see Figure 4).

5.6.1 Gross wrapping stress of wire. The design gross wrapping stress, f_{sg} , the stress in the wire during wrapping, is 75 percent of the specified minimum tensile strength of the wire:

$$f_{sg} = 0.75f_{su}$$

5.6.2 Yield strength of wire. The design yield strength of wire, f_{sy} , is 85 percent of the specified minimum tensile strength of the wire:

$$f_{sy} = 0.85f_{su}$$

This stress level corresponds to the 0.2 percent strain offset in a wire before prestressing.

5.6.3 Modulus of elasticity of wire. The design modulus of elasticity of wire, after wrapping at f_{sg} , for stress levels below f_{sg} , shall be

$$E_s = 28,000,000 \text{ psi (193,050 MPa)}$$

5.6.4 *Stress–strain relationship of wire.** The design stress–strain relationship for prestressing wire, after wrapping at f_{sg} , is shown in Figure 4 and is given in the following equation:

$$\begin{aligned} f_s &= \epsilon_s E_s \text{ for } \epsilon_s \leq f_{sg}/E_s \\ f_s &= f_{su} \{1 - [1 - 0.6133(\epsilon_s E_s / f_{su})]^{2.25}\} \text{ for } \epsilon_s > f_{sg}/E_s \end{aligned} \quad (\text{Eq 5-7})$$

SECTION 6: STRESSES FROM PRESTRESSING[†]

Sec. 6.1 Notation

- A_c = core concrete area, excluding steel-cylinder area (in.²/ft [mm²/m])
- A_s = total area of prestressing wire (in.²/ft [mm²/m])
- A_{sj} = area of the j -th layer of prestressing wire (in.²/ft [mm²/m])
- A_{sf} = area of the final layer of prestressing wire (in.²/ft [mm²/m])
- A_y = steel-cylinder area (in.²/ft [mm²/m])
- C_E = concrete modulus of elasticity multiplier
- C_R = wire intrinsic-relaxation multiplier
- C_s = concrete shrinkage strain multiplier
- C_ϕ = concrete creep factor multiplier
- D_y = outside diameter of steel cylinder (in. [mm])
- E_c = design modulus of elasticity of core concrete (psi [MPa])
- E_s = design modulus of elasticity of prestressing wire (psi [MPa])
- E_y = design modulus of elasticity of steel cylinder (psi [MPa])
- f'_c = design 28-day compressive strength of core concrete (psi [MPa])
- f_{ic} = initial prestress in core concrete (psi [MPa])
- f_{icj} = initial prestress in core concrete after applying the j -th layer of prestressing (psi [MPa])
- f_{cr} = final prestress in core concrete (psi [MPa])
- f_{sg} = gross wrapping stress in prestressing wire = $0.75f_{su}$ (psi [MPa])
- f_{is} = initial stress in a single layer of prestressing wire (psi [MPa])
- f_{isj} = initial stress in the j -th layer of prestressing wire (psi [MPa])
- f_{sr} = final prestress in a single layer of prestressing wire (psi [MPa])
- f_{srj} = final prestress in the j -th layer of prestressing wire (psi [MPa])
- f_{su} = specified minimum tensile strength of prestressing wire (psi [MPa])

* For commentary see appendix A, Sec. A.12.

† For commentary see appendix A, Sec. A.13.

- f_{iy} = initial prestress in steel cylinder (psi [MPa])
 f_{yr} = final prestress in steel cylinder (psi [MPa])
 h_{ci} = thickness of inner core concrete (in. [mm])
 h_{co} = thickness of outer core concrete (in. [mm])
 h_m = thickness of coating, including wire diameter (in. [mm])
 n_i, n_r = modular ratio of prestressing wire to core concrete at wrapping and at maturity, respectively
 n_i', n_r' = modular ratio of steel cylinder to core concrete at wrapping and at maturity, respectively
 P_o = decompression pressure that relieves final prestress in the core concrete (psi [kPa])
 R = wire-relaxation factor for a single layer of prestressing
 R_f = wire-relaxation factor for the outer layer of prestressing
 R_j = wire-relaxation factor for the j -th layer of prestressing
RH = relative humidity (percent)
 s = design shrinkage strain for a buried pipe
 s_{ci}, s_{com}, s_m = shrinkage strain for inner core, outer core and coating, and coating only, respectively
 s_1, s_2 = shrinkage strain for inner core and outer core, respectively, when volume-to-surface correction factor = 1.0
 t_1 = time period of exposure of pipe to outdoor environment (day)
 t_2 = time period of exposure of pipe to burial environment before water filling (day)
 ϕ = design creep factor for a buried pipe
 $\phi_{ci}, \phi_{com}, \phi_m$ = creep factor for inner core, outer core and coating, and coating only, respectively
 ϕ_1, ϕ_2 = creep factor for inner core and outer core, respectively, when volume-to-surface correction factor = 1.0
 γ, γ' = creep and shrinkage volume-to-surface ratio correction factor, respectively
 ρ, ρ' = creep and shrinkage relative humidity correction factor, respectively

Sec. 6.2 Prestress Losses

The state of stress in PCCP is governed by the prestress losses resulting from creep and shrinkage of the concrete and mortar and relaxation of the wire.

Sec. 6.3 State of Stress With a Single Layer of Prestressing

6.3.1 *Initial prestress.* The initial prestress in the concrete core, the steel cylinder, and the prestressing wire is

$$f_{ic} = \frac{A_s f_{sg}}{A_c + n_i A_s + n_i' A_y} \quad (\text{Eq 6-1})$$

$$f_{iy} = n_i' f_{ic} \quad (\text{Eq 6-2})$$

$$f_{is} = -f_{sg} + n_i f_{ic} \quad (\text{Eq 6-3})$$

Where compression is taken as positive, and tension is taken as negative.

6.3.2 *Final prestress.* The final prestress in the concrete, the steel cylinder, and the prestressing wire, after creep and shrinkage of the concrete core and mortar coating and relaxation of the prestressing wire, is

$$f_{cr} = \frac{f_{ic}(A_c + n_r A_s + n_r' A_y) - (A_s E_s + A_y E_y)s - A_s R f_{sg}}{A_c + (n_r A_s + n_r' A_y)(1 + \phi)} \quad (\text{Eq 6-4})$$

$$f_{yr} = f_{iy} + \frac{A_c(f_{ic} \phi n_r' + E_y s) - R A_s f_{sg} n_r'(1 + \phi)}{A_c + (n_r A_s + n_r' A_y)(1 + \phi)} \quad (\text{Eq 6-5})$$

$$f_{sr} = f_{is} + R f_{sg} + \frac{A_c(f_{ic} \phi n_r + E_s s) - R A_s f_{sg} n_r(1 + \phi)}{A_c + (n_r A_s + n_r' A_y)(1 + \phi)} \quad (\text{Eq 6-6})$$

6.3.3 *Decompression pressure.* The decompression pressure, P_o , the pressure that just overcomes the final prestress in the core, is

$$P_o = \frac{f_{cr}(A_c + n_r A_s + n_r' A_y)}{6D_y} \quad (\text{Eq 6-7})$$

Sec. 6.4 State of Stress With Multiple Layers of Prestressing

6.4.1 *Applicability.** This section applies to pipe with multiple layers of prestressing where the clear radial distance between layers is nominally equal to one wire diameter. For designs with greater radial distance between prestressing layers, special designs are required.

6.4.2 *Initial prestress.* The initial prestress in concrete for a pipe with multiple layers of prestressing is the sum of the initial prestress caused by each layer of prestressing:

$$f_{ic} = f_{ic1} + f_{ic2} + f_{ic3} \quad (\text{Eq 6-8})$$

Where:

$$f_{ic1} = \frac{A_{s1} f_{sg}}{A_c + n_i A_{s1} + n_i' A_y} \quad (\text{Eq 6-9})$$

* For commentary see appendix A, Sec. A.14.

$$f_{ic2} = \frac{A_{s2} f_{sg}}{A_c + n_i(A_{s1} + A_{s2}) + n_i' A_y} \quad (\text{Eq 6-10})$$

$$f_{ic3} = \frac{A_{s3} f_{sg}}{A_c + n_i(A_{s1} + A_{s2} + A_{s3}) + n_i' A_y} \quad (\text{Eq 6-11})$$

The initial prestress for each layer of prestressing wire is

$$f_{is1} = -f_{sg} + n_i (f_{ic1} + f_{ic2} + f_{ic3}) \quad (\text{Eq 6-12})$$

$$f_{is2} = -f_{sg} + n_i (f_{ic2} + f_{ic3}) \quad (\text{Eq 6-13})$$

$$f_{is3} = -f_{sg} + n_i f_{ic3} \quad (\text{Eq 6-14})$$

The initial prestress in the steel cylinder is given in Eq 6-2.

6.4.3 Final prestress. The final prestress is given in Eq 6-4 for concrete core and Eq 6-5 for steel cylinder, with $A_s = A_{s1} + A_{s2} + A_{s3}$. The final prestress in the j -th layer of prestressing is

$$f_{srj} = f_{isj} + R_j f_{sg} + \frac{A_c(f_{ic} \phi n_r + E_s s) - \left(\sum_{k=1}^3 R_k A_{sk} \right) f_{sg} n_r (1 + \phi)}{A_c + (n_r A_s + n_r' A_y)(1 + \phi)} \quad (\text{Eq 6-15})$$

6.4.4 Decompression pressure. The decompression pressure for a pipe with multiple layers of prestressing is given in Eq 6-7, with $A_s = A_{s1} + A_{s2} + A_{s3}$.

Sec. 6.5 Modular Ratios

The modular ratios for concrete (where f_c' is in psi) are as follows:

Modular Ratio		Cast Concrete	Spun Concrete
At Wrapping:	n_i	$109(f_c')^{-0.3}$	$100(f_c')^{-0.3}$
	n_i'	$117(f_c')^{-0.3}$	$107(f_c')^{-0.3}$
After Maturity:	n_r	$93(f_c')^{-0.3}$	$95(f_c')^{-0.3}$
	n_r'	$99(f_c')^{-0.3}$	$102(f_c')^{-0.3}$

Where f_c' is in MPa, replace f_c' in the above equations with $145 f_c'$.

Based on the quality-assurance test of concrete modulus of elasticity discussed in Sec. 5.3.4, if the design modulus of elasticity needs to be reduced, then the modular ratios described in this section shall be increased by dividing them by C_E .

Sec. 6.6 Design Creep Factor and Design Shrinkage Strain for Buried Pipe*

For a buried pipe, the creep factor, ϕ , and shrinkage strain, s , are

* For commentary see appendix A, Sec. A.15.

$$\phi = \frac{(h_{co} + h_m)\phi_{com} - h_m\phi_m + h_{ci}\phi_{ci}}{h_{ci} + h_{co}} \quad (\text{Eq 6-16})$$

$$s = \frac{(h_{co} + h_m)s_{com} - h_ms_m + h_{ci}s_{ci}}{h_{ci} + h_{co}} \quad (\text{Eq 6-17})$$

Where ϕ_{ci} , ϕ_{com} , ϕ_m , s_{ci} , s_{com} , and s_m are creep factors and shrinkage strains for the inner core, the outer core plus the coating, and for the coating, respectively.

Based on the quality-assurance tests of concrete creep and shrinkage discussed in Sec. 5.3.6, if the design creep factor and shrinkage strain need to be increased, the values of ϕ and s computed in Eq 6-16 and 6-17 shall be multiplied by C_ϕ and C_s , respectively.

The volume-to-surface ratio of a cylinder with only one exposed surface is equal to its thickness. Creep factors and shrinkage strains are expressed in terms of volume-to-surface ratios as follows:

$$\phi_{ci} = \phi_1\gamma(h_{ci}) \quad (\text{Eq 6-18})$$

$$\phi_{com} = \phi_2\gamma(h_{co} + h_m) \quad (\text{Eq 6-19})$$

$$\phi_m = \phi_2\gamma(h_m) \quad (\text{Eq 6-20})$$

and

$$s_{ci} = s_1\gamma'(h_{ci}) \quad (\text{Eq 6-21})$$

$$s_{com} = s_2\gamma'(h_{co} + h_m) \quad (\text{Eq 6-22})$$

$$s_m = s_2\gamma'(h_m) \quad (\text{Eq 6-23})$$

Where γ and γ' are volume-to-surface correction factors for creep and shrinkage.

ϕ_1 , s_1 , ϕ_2 , and s_2 are the creep factors and shrinkage strains for inner core concrete and outer core concrete for the special case of $\gamma = \gamma' = 1.0$. The functions $\gamma(h)$ and $\gamma'(h)$ of the volume-to-surface ratio h are:

$$\gamma(h) = \frac{2}{3}[1 + 1.13e^{-0.54h}] \quad (\text{Eq 6-24})$$

$$\gamma'(h) = 1.2e^{-0.12h} \quad (\text{Eq 6-25})$$

Values of ϕ_1 , ϕ_2 , s_1 , and s_2 are determined on the basis of the following design scenario for exposure of buried pipe:

1. The inner and outer surfaces of the pipe are exposed to an outdoor environment with a specific relative humidity, RH, for t_1 days.
2. The inner and outer surfaces of the pipe are exposed to a burial environment with 92.5 percent RH for an additional t_2 days.

3. The inner surface of the pipe is exposed for the remainder of the pipe's service life to a 100 percent RH environment (water-filled condition), while the outer surface continues to be exposed to the burial environment.

The minimum values of t_1 and t_2 for which the pipe shall be designed are

$$t_1 = 270 \text{ days (9 months)}$$

$$t_2 = 90 \text{ days (3 months)}$$

Longer exposure periods may be specified by the purchaser.

Values for ϕ_1 , ϕ_2 , s_1 , and s_2 are given in the following table for $t_1 = 270$ days, $t_2 = 90$ days, and two different relative humidities of the preburial environment. The design relative humidity before burial may not exceed 70 percent. For a design relative humidity between 70 and 40 percent, the constants ϕ_1 , ϕ_2 , s_1 , and s_2 shall be computed by linear interpolation between the values given in the table. For a design relative humidity less than 40 percent, the constants ϕ_1 , ϕ_2 , s_1 , and s_2 shall be those given in the table for RH = 40 percent.

Constant	Cast Core		Spun Core	
	RH = 70%	RH = 40%	RH = 70%	RH = 40%
ϕ_1	1.76	2.12	1.06	1.27
ϕ_2	1.79	2.14	—	—
s_1	184×10^{-6}	262×10^{-6}	111×10^{-6}	157×10^{-6}
s_2	299×10^{-6}	377×10^{-6}	—	—

Values of ϕ_1 , ϕ_2 , s_1 , and s_2 for cast core concrete when $t_1 \neq 270$ days or $t_2 \neq 90$ days may be calculated from the following expressions:

$$\phi_1 = 2.35 \left[\frac{\rho - 0.65}{1 + 10/t_1^{0.6}} + \frac{0.05}{1 + 10/(t_1 + t_2)^{0.6}} + 0.6 \right] \quad (\text{Eq 6-26})$$

$$\phi_2 = 2.35 \left[\frac{\rho - 0.65}{1 + 10/t_1^{0.6}} + 0.65 \right] \quad (\text{Eq 6-27})$$

$$s_1 = 312 \times 10^{-6} \left[\frac{(\rho' - 0.225) t_1}{t_1 + 55} + \frac{0.225(t_1 + t_2)}{t_1 + t_2 + 55} \right] \quad (\text{Eq 6-28})$$

$$s_2 = 780 \times 10^{-6} \left[\frac{(0.4 \rho' - 0.09) t_1}{t_1 + 55} + 0.225 \right] \quad (\text{Eq 6-29})$$

Where:

$\rho = 0.8$ and $\rho' = 0.7$ for RH = 70 percent

$\rho = \rho' = 1.0$ for RH = 40 percent