Louisiana Transportation Research Center

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Literature Search on Use of Flexible Pipes in Highway Engineering for DOTD's Needs

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13. Abstract

Drainage in Louisiana transportation projects are critical components in pavement infrastructure and are typically addressed using rigid concrete pipes. Plastic pipes include many various polymer-based materials, e.g., high-density polyethylene (HDPE), polyvinyl chloride (PVC), and polypropylene (PP). A long-term track record of rigid concrete pipe performance is available to DOTD, but limited information is available on plastic pipes. A better understanding of the applications, limitations, and advantages of plastic pipes can help DOTD facilitate the design, construction, and maintenance of pavement infrastructure beyond traditional methods. As a result, the research objective of this study was to determine where, when, and how DOTD can use plastic pipes. The long-term goal is to include plastic pipes into the DOTD materials specifications such that it is an option for engineers, designers, and contractors. DOTD specifications provide guidance for the appropriate implementation of thermoplastic pipes used for cross drains, side drains, and storm drains that follows the state-of-practice. A 70-year design life can be used for highways ordinarily requiring 50-year design life if the fill height on the cross drain is greater than 10 ft. Florida DOT has implemented a 100-year design life for polypropylene pipe if the extensive requirements in their specifications are met, which are based on slow crack growth resistance

testing and tests to verify that the anti-oxidant package would last longer than the desired design life. In addition, FDOT has also implemented similar testing for a 100-year design life HDPE pipe. Other states, such as Texas, Kansas, and Minnesota, also permit PP to be used in cross-drain applications but they impose ADT limits (Texas < 2000, Kansas < 3000, and Minnesota < 5000). As a result, the outcome of this survey of other state agencies indicates that PP pipe can be used in Louisiana as outlined in the next version of EDSM guidelines (in preparation), where PP is allowed to replace corrugated polyethylene pipe double wall (CPEPDW). CPEPDW is currently used for cross drain (service life of 50 years) and side drains (service life 30 years except for bridge drains that are 50 years), where the traffic volume is less than 3,000. If a longer service life is considered, the testing protocol should follow Florida DOT because it uses stress crack resistance and antioxidant depletion for evaluating long-term performance. Field performance documentation is also necessary to substantiate post-installation and long-term performance. This will provide feedback to the design engineers at DOTD on performance. In particular, for all the considered plastic material pipes, the design deflection value is lower than the allowable when using the initial modulus of pipe material. When using the long-term modulus value, the deflection increases towards the limits of compressive strain for both HDPE and PP pipes. These design values and calculations can help to grasp how the different pipe materials might perform in practice, but experimental (field and laboratory) data is advised.

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Abstract

Drainage in Louisiana transportation projects are critical components in pavement infrastructure and are typically addressed using rigid concrete pipes. Plastic pipes include many various polymer-based materials, e.g., high-density polyethylene (HDPE), polyvinyl chloride (PVC), and polypropylene (PP). A long-term track record of rigid concrete pipe performance is available to DOTD, but limited information is available on plastic pipes. A better understanding of the applications, limitations, and advantages of plastic pipes can help DOTD facilitate the design, construction, and maintenance of pavement infrastructure beyond traditional methods. As a result, the research objective of this study was to determine where, when, and how DOTD can use plastic pipes. The long-term goal is to include plastic pipes into the DOTD materials specifications such that it is an option for engineers, designers, and contractors. DOTD specifications provide guidance for the appropriate implementation of thermoplastic pipes used for cross drains, side drains, and storm drains that follows the state-of-practice. A 70-year design life can be used for highways ordinarily requiring 50-year design life if the fill height on the cross drain is greater than 10 ft. Florida DOT has implemented a 100-year design life for polypropylene pipe if the extensive requirements in their specifications are met, which are based on slow crack growth resistance testing and tests to verify that the anti-oxidant package would last longer than the desired design life. In addition, FDOT has also implemented similar testing for a 100-year design life HDPE pipe. Other states, such as Texas, Kansas, and Minnesota, also permit PP to be used in cross-drain applications but they impose ADT limits (Texas < 2000, Kansas < 3000, and Minnesota < 5000). As a result, the outcome of this survey of other state agencies indicates that PP pipe can be used in Louisiana as outlined in the next version of EDSM guidelines (in preparation), where PP is allowed to replace corrugated polyethylene pipe double wall (CPEPDW). CPEPDW is currently used for cross drain (service life of 50 years) and side drains (service life 30 years except for bridge drains that are 50 years), where the traffic volume is less than 3,000. If a longer service life is considered, the testing protocol should follow Florida DOT because it uses stress crack resistance and antioxidant depletion for evaluating long-term performance. Field performance documentation is also necessary to substantiate post-installation and long-term performance. This will provide feedback to the design engineers at DOTD on performance. In particular, for all the considered plastic material pipes, the design deflection value is lower than the allowable when using the initial modulus of pipe material. When using the long-term modulus value, the deflection increases towards the limits of compressive strain for both HDPE and PP pipes. These design values and calculations can help to grasp how the different pipe materials might perform in practice but experimental (field and laboratory) data is advised.

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Implementation Statement

This report is intended to provide a comprehensive background on the applicability of thermoplastic pipes for cross drains, storm drains, and side drains on highway engineering projects. The outcome of this research will aid DOTs to understand when, what type, and the limitations of thermoplastic pipes for different applications.

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Introduction

The Louisiana Department of Transportation and Development (DOTD), through the Louisiana Standard Specifications of Roads and Bridges (herein referred to specifications) [*1*], gives a thorough guideline to what is required for the implementation of pipes for culverts and storm drains. The design procedures, design criteria, and implementation process for plastic pipes have been widely investigated and thus, the use of plastic pipes for various types of drains is becoming more popular and adopted by several states around the United States.

This report presents the requirements and specifications for the use of concrete and plastic pipes in Louisiana and near states, the research completed in recent years regarding the design procedures and acceptance criteria for the use of plastic pipes for storm drains and culverts, and provides details of the current practice and adoption of other state departments of transportation. Additionally, a comparison between the implementation of concrete versus plastic pipes and recommendations of when plastic pipes should be used for the different drainage applications in transportation projects is included. The information herein presented is divided into five tasks:

- Task 1 — Provide a historical summary of the DOTD specifications for culverts and storm drains to document the criteria for making decisions in pipe selections. The outcome of this task is to provide a baseline of what was previously recommended and what criteria are important in drainage applications.
- Task 2 — Synthesize the current literature on plastic pipe research from Louisiana and other states, and various National Cooperative Highway Research Program (NCHRP) reports. This task involves a comprehensive literature review on plastic pipes and their application to transportation drainage systems.
- Task 3 — Survey other state DOTs with similar soils, environments, and situations. This task involves state-of-practice for other DOT agencies. For example, practices at Texas, Kentucky, Virginia, Tennessee, Minnesota, Alabama, Illinois, Arkansas, Georgia, and Florida were investigated.
- Task 4 — Compare the performance of concrete and plastic pipes, along with associated installation requirements. The comparison will be made in terms of plastic and rigid pipe dimensions, cover, bedding, backfill, structural capacity and loading criteria, transportation to the site, QA/QC inspection procedure, service life, application, excavation geometry, maintenance, and all the make and models of plastic pipes.
- Task 5 — Synthetization of the lessons learned in Tasks 1 – 4 and recommendations as to how best utilize plastic pipes as an available alternative in drainage applications.

Definitions

- Bridge — A structure, including supports, erected over a depression or an obstruction, such as water, a highway, or a railroad, which has a track or passageway for carrying traffic or other moving loads; and has an opening measured along the center of the roadway or more than 20 ft. between undercopings of abutments, spray lines or arches, or extreme ends of openings for multiple boxes. A bridge may include multiple pipes where the clear distance between openings is less than one-half the smaller contiguous opening.
- Cross drain — Also referred to as culverts, cross drains run perpendicular and under roads. Their main function is to lead water from the higher ground on one side of the road to lower ground on the other side of the road.
- Culvert — Any drainage structure under a roadway or other facility not defined as a bridge.
- Side drain — Also referred to as ditches, side drains run parallel to roads and their main function is to collect water from the road and other surrounding areas.
- Storm drain — A fully contained and connected set of drainage structures, which capture the rainwater runoff from the transportation system.
- Underdrains — A drainage feature installed underground to collect subsurface water and transport it to a surface outlet.

Scope

Drainage in Louisiana transportation projects are critical components in pavement infrastructure and are typically addressed using rigid concrete pipes. Plastic pipes include many various polymer-based materials, e.g., high-density polyethylene (HDPE), polyvinyl chloride (PVC), and polypropylene (PP) among others. A long-term track record of rigid concrete pipe performance is available to DOTD, but limited information is available on plastic pipes. A better understanding of the applications, limitations, and advantages of plastic pipes can help DOTD facilitate the design, construction, and maintenance of pavement infrastructure beyond traditional methods.

The overarching research objective is to determine where, when, and how DOTD can use plastic pipes. The long-term goal is to include plastic pipes into the DOTD materials specifications such that it is an option for engineers, designers, and contractors. The specific aims for this literature search include the following:

1. Provide a historical summary of the DOTD specifications for culverts and storm drains to document the criteria for making decisions in pipe selections.
2. Synthesize the current literature on plastic pipe research from Louisiana and other states.
3. Survey other state DOTs with similar soils, environments, and situations.
4. Compare the performance of concrete and plastic pipes, along with associated installation requirements.
5. Provide recommendations for DOTD on where and when to allow the use of each type of plastic pipe in drainage applications, required installation procedures, and limitations associated with plastic pipes.

Literature Review

Task 1. Historical Summary of DOTD Specifications

The document provides general guidelines for excavation and backfilling of the excavated soil, specifications on types of pipes that can be used (along with its reinforcement, thickness, and other characteristics in the case of concrete); characteristics of the soil to be used for bedding and backfilling the excavation; and geometrical requirements for the trench where the pipe will be placed. These specifications have been modified since the release of the first version in 1929 to the most recent one in 2016.

Throughout all the Specification versions, it is found that all excavations of drainage ditches are to be made before the pavement is laid, and all roots and foreign matter from sides and bottom shall be cut to conform slope, grade, and shape of the section. Care must be taken for the deposition of the excavated material, as it must be placed according to the engineer's directions and always at least 3 ft. away from the edge of the ditch.

The specifications for concrete pipes for storm drains were regulated in each of the versions of the DOTD specifications from 1929 to 1955, with a standard compressive strength of 3500 psi or 4500 psi. From 1966 to the present, the ASTM C76 Standard [*2*] was adopted to determine the specifications for concrete pipes, their minimum wall thickness, concrete compressive strength, and minimum reinforcement. The 4000 psi Class III Reinforced Concrete Pipe is the standard for culverts and storm drains applications. ASTM C76 [*2*] specifies three types of wall thickness for Class III Reinforced concrete pipe (Wall A, B, or C). Each has an increasing wall thickness for the same internal diameter. As per DOTD requirement, either wall thickness can be chosen. When joining two concrete pipes, the specifications require that a bell and spigot or tongue and groove should be used. Ends should be fully centered and inner surfaces must be flush and even. Finally, an appropriate seal with gasket material must also be installed. In previous versions of the specifications, mortar was mostly used.

It was until 1977 that the DOTD specifications included plastic pipes as an alternative for underdrains, specifically including corrugated polyethylene (PE) (AASHTO M252 [*3*]) or polyvinyl chloride (PVC) (ASTM D3034). The newest version of the specifications broadens the use of plastic pipes for culverts and storm drains. The materials list is also broadened and can include polyvinyl chloride pipe (PVCP) (ASTM D3034 [*4*]), ribbed polyvinyl chloride pipe (RPVCP) (ASTM F794 [*5*]), corrugated polyethylene pipe single wall (CPEPSW) (AASHTO

M252 [*3*]), and corrugated polyethylene pipe double wall (CPEPDW) (AASHTO M294 [*6*]). Joining two plastic pipes must be done through bell and spigot or split coupling bands. Ends should be fully centered and inner surfaces must be flush and even. A seal with gasket material must be installed to avoid any leakage or filtration into the surrounding soil.

The soil material specifications for backfilling have changed throughout the years, but they retained the core concept of selecting compactable material and limiting excessive moisture. Earlier standards suggested materials conforming to AASHTO specifications (A-1-a, A-1-b, A-2-4, A-2-5, A-3 or A-4 or A-6 in 1971) to usable or selected (also referred as Type B) materials in the most recent versions of the specifications. Usable materials are those with plasticity index (PI) less than 25, organic content (OC) less than 5%, and silt content less than 50%. In contrast, selected materials consist of PI less than 20, liquid limit (LL) less than 35, OC less than 5%, and silt content less than 50%. Though not explicitly stated in the specifications, it is interpreted that selected soils are preferred for better engineering properties and hence performance. However, if not available, usable soils can be employed instead. Backfilling is required to cover 1 ft. over the top of the pipe. In cases where the pipe will be subjected to construction traffic, the pipe backfill must be at least 2 ft. on top of the pipe. The moisture content of the soil must be controlled, and compaction must be made in lifts of less than 8 in. and up to 12 in. if permitted by the engineer, in such a manner that 95% of maximum dry density is obtained, either by nuclear method or by a sand cone in accordance with DOTD TR 401. Historically, compaction lifts were required to be less than 6 in. but the most recent versions permit thicker lifts. An explanation is not provided in the specifications for increasing the thickness of lifts.

All the specification versions require that the excavation be carried to the required depth according to the design pipe invert. The width of the trench must be enough to allow adequate compaction and workspace. Previous versions required that the trench had to be excavated wide enough to allow adequate compaction and working space but no more than 12 in. on both sides of the pipe. Most recent versions require that 18 in. on each side of the pipe must be excavated and compacted. If rock is encountered at the bottom of the excavated trench, it must be removed and replaced with at least 8 in. of Type A (stone, recycled Portland cement concrete, flowable fill, or reclaimed asphalt pavement (RAP)) or granular material to accommodate the pipe.

The requirements presented in Task 1, according to the specifications, are general whether concrete or plastic pipe is chosen for a specific application. Table 1 shows a summary of the main requirements of the DOTD specifications. Table 2 shows a comparison of soil materials defined in DOTD and AASHTO specifications. Table 3 presents the gradation for stone, recycled Portland cement concrete, and RAP materials for bedding and backfill for pipe installations. Tables 4, 5, and 6 present the wall thickness and minimum steel reinforcement for concrete pipe as referenced in Table 1 for the previous and most recent version of the specification.

Table 1. Summary of requirements of most recent and previous DOTD specifications

Requirement	Previous DOTD Specifications	2016 DOTD Specifications
General	Excavate drainage ditches before the pavement is laid. No deviation from alignment grade or section. All roots and foreign matter from sides and bottom shall be cut to conform slope, grade, and shape of the section.	Excavate drainage ditches before the pavement is laid. No deviation from alignment grade or section. All roots and foreign matter from sides and bottom shall be cut to conform slope, grade, and shape of the section.
Deposition	Deposition of material according to engineer's directions. No excavation material shall be left less than 3 ft. of the edge of the ditch	Deposition of material according to engineer's directions. No excavation material shall be left less than 3 ft. of the edge of the ditch
Concrete pipe	Table 2 and 3	Class III, Wall A, B or C (Table 4, ASTM C76)
Joints	Mortar joints	Bell and spigot / tongue and groove
Min. thickness	Table 2 and 3	Class III, Wall A, B or C (Table 4, ASTM C76)
Min. reinforcement	Table 2 and 3	Class III, Wall A, B or C (Table 4, ASTM C76)
Plastic pipe	—	Corrugate Polyethylene (AASHTO M 252) / PVC (ASTM D 3034)
Joints	—	Bell and spigot / split coupling bands
Materials	A-1-a, A-1-b, A-2-4, A-2-5, A-3 or A-4 or A-6	Usable: PI < 25, OC < 5%, silt < 50%
		Selected: PI < 20, LL < 35, OC < 5%, silt < 50% (Type B) (see Table 2)
Trench width	Enough to allow compaction. Not exceeding 12 in. on each side	18 in. on each side of the pipe

Trench bottom	If rock encountered on the bottom, excavate and place loose soil at least 8 in.	If rock encountered on the bottom, excavate and place loose soil at least 8 in.
Backfilling	A-1-a, A-1-b, A-2-4, A-2-5, A-3 or A-4 or A-6	Type B (see Table 2)
	Backfill to 1 ft. on top of the pipe	Backfill to 1 ft. on top of the pipe, up to 2 ft. in some cases
	Selected embankment material, lifts < 6 in.	Compact in layers of < 8 in., 95% of max density for selected (Type B) soils
	—	May be allowed by engineer to compact in layers of < 12 in., 95% of max density for selected (Type B) soils

Table 2. Soil type comparison (DOTD and AASHTO)

Material type	DOTD	AASHTO
Stone, recycled Portland cement concrete, flowable fill, or RAP	Type A	See gradation in Table 3
Select soils defined as natural soils with PI < 20, LL < 35, OC < 5%	Type B	A-2-4, A-2-5, A-4, A-6
PI: plasticity index		
LL: liquid limit		
OC: organic content		

Table 3. Stone, recycled Portland cement concrete, and RAP gradation for bedding and backfill

Bedding/backfill	
Stone Gradation	
US (metric) sieve size	**Percent passing by weight (mass)**
1-1/2" (37.5 mm)	100
1" (25 mm)	90 - 100
3/4" (19 mm)	70 - 100
No. 4 (4.75 mm)	35 - 65
No. 40 (425 µm)	12 - 32
No. 200 (75 µm)	5 - 12
Recycled Portland Cement Concrete Gradation	
US (metric) sieve size	**Percent passing by weight (mass)**
1-1/2" (37.5 mm)	100
1" (25 mm)	90 - 100
3/4" (19 mm)	70 - 100
No. 4 (4.75 mm)	35 - 65
No. 40 (425 µm)	12 - 32
No. 200 (75 µm)	0 - 8
Backfill	
Reclaimed Asphalt Pavement (RAP)	
US (metric) sieve size	**Percent passing by weight (mass)**
2" (50 mm)	100
No. 4 (4.75 mm)	35 - 75

Table 4. Previous concrete specifications (standard strength concrete)

	3,500 psi Concrete		**4,500 psi Concrete**		**Strength Test Requirement (lb/ft. pipe)**	
Internal diameter (in.)	Minimum Thickness of shell (in.)	Minimum circular reinforcement, (in.^{2}/ft. of pipe)	Minimum Thickness of shell (in.)	Minimum circular reinforcement, (in.^{2}/ft. of pipe)	Load for 0.01-in. crack	Ultimate Load
12	2	1 line - 0.07	1-3/4	1 line - 0.08	2,500	3,500
15	2-1/4	1 line - 0.09	2	1 line - 0.11	2,620	4,065
18	2-1/2	1 line - 0.12	2-1/4	1 line - 0.14	3,000	4,500
24	3	1 line - 0.17	2-1/2	1 line - 0.20	3,000	5,000
30	3-1/2	2 lines - each 0.17	3	1 line - 0.28	3,375	5,750
36	4	2 lines - each 0.18	3-3/8	2 lines - each 0.22	4,050	6,600
42	4-1/2	2 lines - each 0.21	3-3/4	2 lines - each 0.25	4,725	7,350
48	5	2 lines - each 0.25	4-1/4	2 lines - each 0.31	5,400	8,000
54	5-1/2	2 lines - each 0.30	4-5/8	2 lines - each 0.37	5,850	9,000
60	6	2 lines - each 0.33	5	2 lines - each 0.41	6,000	10,000
72	7	2 lines - each 0.40	6	2 lines - each 0.48	6,600	12,000
84	8	2 lines - each 0.46	7	2 lines - each 0.54	7,000	14,000
The spacing of circular reinforcement shall not exceed 4 in. center-to-center for pipes up to 48 in.						

Table 5. Previous concrete specifications (extra strength concrete)

	4,500 psi Concrete		**Strength Test Requirement (lb/ft. pipe)**	
Internal diameter (in.)	Minimum Thickness of shell (in.)	Minimum circular reinforcement, (in.^{2}/ft. of pipe)	Load for 0.01-in. crack	Ultimate Load
24	3	1 line - 0.26	4,000	6,000
30	3-1/2	1 line - 0.31	5,000	7,500
36	4	2 lines - each 0.28	6,000	9,000
42	4-1/2	2 lines - each 0.33	7,000	10,500
48	5	2 lines - each 0.38	8,000	12,000
54	5-1/2	2 lines - each 0.44	9,000	13,500
60	6	2 lines - each 0.50	9,000	15,000
66	6-1/2	2 lines - each 0.56	9,500	16,500
72	7	2 lines - each 0.60	9,900	18,000
84	8	2 lines - each 0.72	10,500	21,000
The spacing of circular reinforcement shall not exceed 4 in. center-to-center for pipes up to 48 in.				

Table 6. ASTM C76 design requirements for class III reinforced concrete pipe

4,000 PSI Concrete, Wall A			
Internal diameter (in.)	Wall Thickness (in.)	Circular reinforcement, inner cage (in.^{2}/ft. of pipe)	Circular reinforcement, outer cage (in.^{2}/ft. of pipe)
12	1-3/4	0.07	—
15	1-7/8	0.07	—
18	2	0.07	—
21	2-1/4	0.14	—
24	2-1/2	0.17	—
27	2-5/8	0.18	—
30	2-3/4	0.19	—
33	2-7/8	0.21	—
36	3	0.21	0.12
42	3-1/2	0.24	0.15
48	4	0.32	0.19
54	4-1/2	0.38	0.23
60	5	0.44	0.26
66	5-1/2	0.50	0.30
72	6	0.57	0.34
4,000 PSI Concrete, Wall B			
Internal diameter (in.)	Wall Thickness (in.)	Circular reinforcement, inner cage (in.^{2}/ft. of pipe)	Circular reinforcement, outer cage (in.^{2}/ft. of pipe)
12	2	0.07	—
15	2-1/4	0.07	—
18	2-1/2	0.07	—
21	2-3/4	0.07	—
24	3	0.07	—
27	3-1/4	0.16	—
30	3-1/2	0.18	—
33	3-3/4	0.20	—
36	4	0.17	0.10
42	4-1/2	0.21	0.12
48	5	0.24	0.14
54	5-1/2	0.29	0.17
60	6	0.34	0.20
66	6-1/2	0.41	0.24
72	7	0.49	0.29

4,000 PSI Concrete, Wall C			
Internal diameter (in.)	Wall Thickness (in.)	Circular reinforcement, inner cage (in.^{2}/ft. of pipe)	Circular reinforcement, outer cage (in.^{2}/ft. of pipe)
12	2-3/4	0.07	—
15	3	0.07	—
18	3-1/4	0.07	—
21	3-1/2	0.07	—
24	3-3/4	0.07	—
27	4	0.08	—
30	4-1/4	0.10	—
33	4-1/2	0.12	—
36	4-3/4	0.08	0.07
42	5-1/4	0.12	0.07
48	5-3/4	0.16	0.10
54	6-1/4	0.21	0.12
60	6-3/4	0.24	0.15
66	7-1/4	0.31	0.19
72	7-3/4	0.36	0.21
D-load to produce a 0.01-in. crack: 1350 pounds-force per linear foot per foot of diameter[1]			
D-load to produce a 0.01-in. crack: 2000 pounds-force per linear foot per foot of diameter[1]			
[1]Multiply by the internal diameter of the pipe in feet			

Task 2. Literature Review on Plastic Pipe Research

NCHRP Report 438

Report 438 [*7*] of the National Cooperative Highway Research Program (NCHRP) provides recommendations on LRFD Specifications for Plastic Pipe and Culverts. The report focuses on the compression capacity of profile wall plastic pipe and the resistance of the pipe to failure by local buckling. Several research projects [*8*, *9*] performed compression, parallel plates, and hoop compression tests and are discussed below.

Zhang and Moore [*8*] performed tests in which polyethylene (PE) pipes were subject to compression tests at different strain rates. The tests demonstrated that the compression behavior was independent of strain rate, i.e., similar stress-strain relationships were observed. All strain rates show relatively linear stress-strain curve up to 2% strain, relatively flat strain above 6% strain, and yield in compression in the range of 15%. Therefore, they recommended that the design of plastic pipe to be based on a strain limit rather than a stress limit, and the limit is recommended to be set in the range of 4% to 6%.

The American Association of State Highway and Transportation Officials (AASHTO) specifications require that pipes must be subjected to a flattening test per ASTM D2412 [*10*]. In this test, polyethylene (PE) pipe specimens are flattened between two parallel plates in a press until the vertical distance between the plates is 20% of the outer diameter of the pipe. For polyvinyl chloride (PVC) pipes, the vertical distance between plates must be 60% of the outer diameter of the pipe. In both cases, the specified deflection of the pipes must be achieved without showing any signs of buckling, cracking, or other loss of load-carrying capacity. Several manufacturers performed these tests and the results show that at 20% deflection, PE pipes reached strain levels ranging from 2.5 – 5.5% on the inside and 4.5% – 10% on the outside. Because the parallel plates touch the pipe on the outside and may provide support or restrain it from reaching higher levels of strain, only the inside strain levels are considered when comparing to the limits established by AASHTO. Table 7 provides a summary of the strain limits set by AASHTO. The results showed that the pipes perform well and have acceptable strains under 20% deflection. Selig et al. [*9*] performed long-term parallel plate tests in PE pipes in which 5%, 10%, and 15% deflections were held for a year. Results show that at 15% deflection, no signs of failure were observed, including local buckling.

Table 7. Apparent strain limits based on AASHTO properties for HDPE and PVC [*7*]

Material	**HDPE**				**PVC**			
Resin	335420C		334433C		12454C		12364C	
Design Period	Short	Long	Short	Long	Short	Long	Short	Long
Strength, MPa	21	6.2	21	7.7	48	25	41	18
Modulus, MPa	760	152	551	138	2760	965	3030	1090
Compression Strain	2.8%	4.1%	3.8%	5.6%	1.7%	2.6%	1.4%	1.7%
AASHTO	5.0%		5.0%		5.0%		3.5%	

Hoop compression tests were also performed by Selig et al. [*9*]. The tests are determined by placing the pipe in a steel cylinder with an inflatable bladder. The space between the cylinder and the pipe is filled with soil and then the bladder is inflated. This causes diameter changes, which are related to circumferential stresses. In PE pipes, strain levels between 2.2% and 4% were observed. One of the tests reported buckling at a strain level of 3%. No PVC pipes were tested for this study.

NCHRP 438 [*7*] also inspected pipes in the ground to check for any distress. Although some cases of local buckling were observed, no buckling or compressive failure was recorded unless deflections are greater than 15%.

Seminal work by George Bryan and George Winter on metal plates serve as a valuable surrogate to understand the behavior of plastic pipe walls. Bryan [*11*] developed research on buckling of thin wall metal sections. According to the research, the critical buckling stress depends mainly on the material modulus of elasticity, width-to-thickness (w/t) ratio of the metal plate, and edge support conditions. The edge support coefficient varied from 0.43 (free edge, i.e., no support at all on one of the edges) to 4 (plate with edges simply-supported). The edge support coefficient can reach a value of 7 if the edges are both fixed against rotation. Winter [*12*] noted that even after buckling, the metal plates still had enough capacity to withhold the loads and proposed a method to consider this additional capacity. The method is called the "effective width approach" and its premise is that the center portion of the plate will not contribute to the overall capacity once buckling has occurred. Nonetheless, the edges will remain effective and resist the applied load on the plate.

The NCHRP Report 438 includes test specimens to perform compression tests and determine the buckling capacity of the pipes. The specimens were cut from corrugated PE and PVC pipes and included three corrugations or periods. Figure 1 shows the configuration of the test specimens. The specimens' ends were made smooth with a belt sander but were not milled to perfect parallel ends. Samples with various width/thickness ratios and lengths and a 100 kN universal compression/tension machine were used for the tests. Figure 2 presents a summary of the width/thickness ratio of the pipe sections tested. Vertical load and lateral and vertical displacements were measured for each specimen. The end conditions for the specimens varied from neoprene bearing pads to plaster encasement, to no special provisions (direct bearing on end plate). Although most of the end conditions showed to be time consuming or ineffective, conducting the test with the direct bearing on the end plate proved to be the most reliable. The arc length of the specimens varied and the longer the arc length, the more deflection was recorded. It was observed that these longer specimens were initially stressed in bending and its inner surface subject to compression. Shorter specimens were subjected only to compression. After buckling occurred in some cases, the section of the specimen was no longer fully effective and therefore Winter's approach was used to estimate the peak strain. This is important to understand how the peak strain was calculated, i.e., even after buckling has occurred, the edges of the pipe remain effective and thus contribute to the overall strength.

Figure 1. Test specimen configuration [*7*]

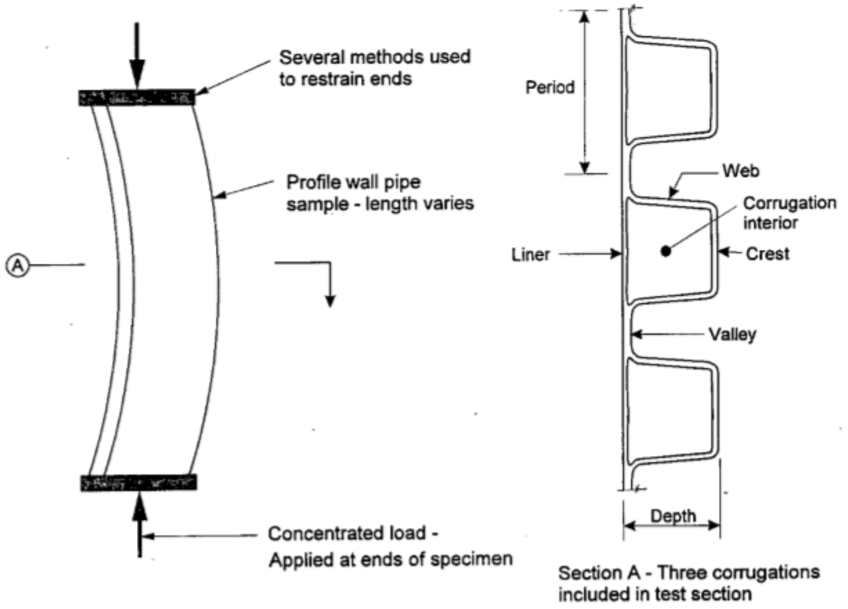
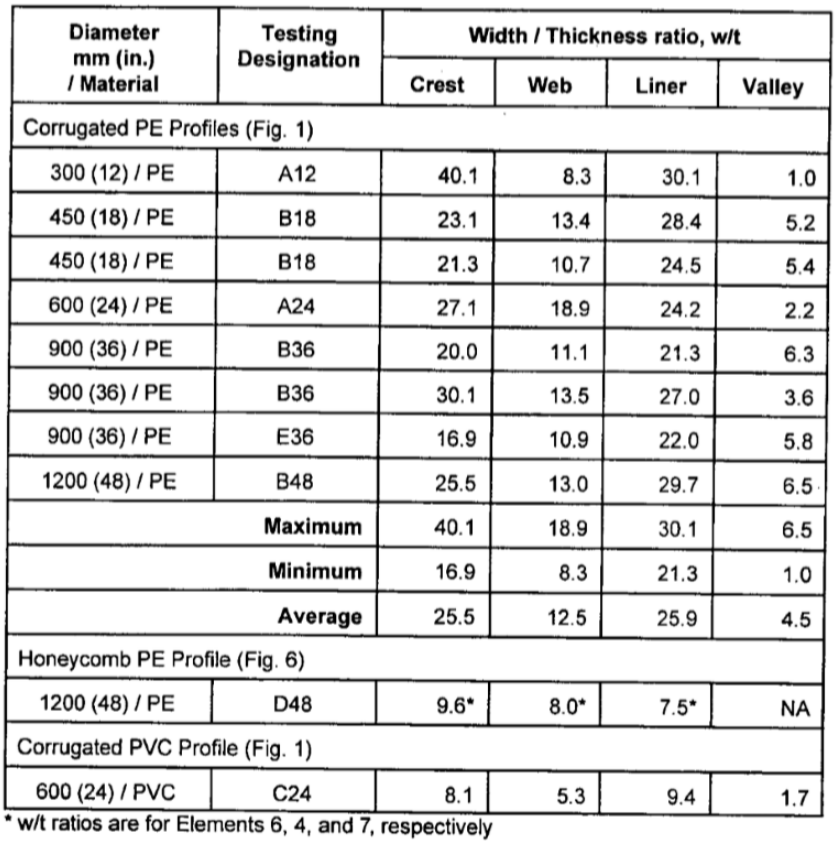


Figure 2. Width/thickness ratio of pipe specimens [*7*]

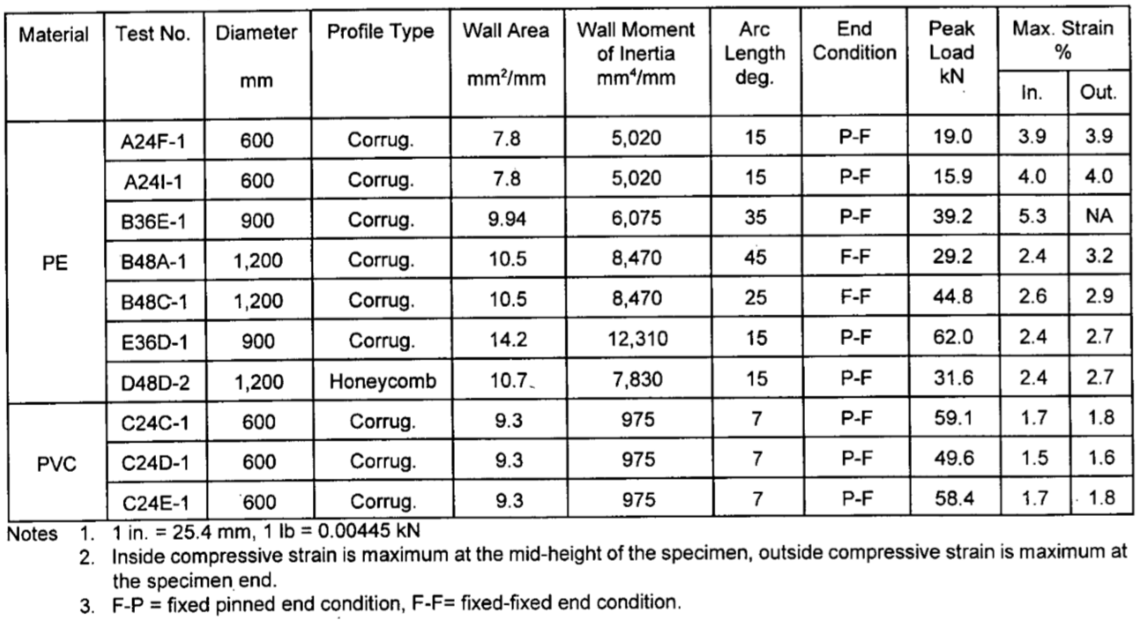


Diameter mm (in.) / Material	Testing Designation	Width / Thickness ratio, w/t			
		Crest	Web	Liner	Valley
Corrugated PE Profiles (Fig. 1)					
300 (12) / PE	A12	40.1	8.3	30.1	1.0
450 (18) / PE	B18	23.1	13.4	28.4	5.2
450 (18) / PE	B18	21.3	10.7	24.5	5.4
600 (24) / PE	A24	27.1	18.9	24.2	2.2
900 (36) / PE	B36	20.0	11.1	21.3	6.3
900 (36) / PE	B36	30.1	13.5	27.0	3.6
900 (36) / PE	E36	16.9	10.9	22.0	5.8
1200 (48) / PE	B48	25.5	13.0	29.7	6.5
	Maximum	40.1	18.9	30.1	6.5
	Minimum	16.9	8.3	21.3	1.0
	Average	25.5	12.5	25.9	4.5
Honeycomb PE Profile (Fig. 6)					
1200 (48) / PE	D48	9.6*	8.0*	7.5*	NA
Corrugated PVC Profile (Fig. 1)					
600 (24) / PVC	C24	8.1	5.3	9.4	1.7

* w/t ratios are for Elements 6, 4, and 7, respectively

AASHTO provides design values for strength and stiffness and its applicability to the compressive strength of pipes. The results of the tests from Figure 2 conducted on PE and PVC show that the values are congruent with the AASHTO values. When a specimen is subject to bending and compression, its resistance to buckling will decrease compared to a specimen subjected to bending only. This occurs because when only bending is present, the center section of the specimen does not buckle, and this increases the overall compression capacity. Additional compression tests with strain-gauged specimens were performed. The purpose of these tests was to further investigate the pipes' behavior under compression and to verify that the linear elastic theory for curved beams was applicable to evaluate the test results. Corrugated PVC and corrugated HDPE specimens were selected for this test, as in the original tests. The specimens were instrumented, and three end conditions were evaluated: fixed-fixed, fixed-free, and free-free. Following the same pattern as the previous compression tests, the specimens included three full corrugations but the arc length of each was the same. Four gauges were bonded to the mid-point and other four to the quarter-point of the specimens (one to the crest and another to the liner of the middle corrugation, and one to each side of the valleys of the middle corrugation). The tests were carried out to a maximum strain level of 1%. The results were evaluated using linear elastic curved beam theory. The total stresses along the arc length were determined with the axial loads and moments acting on the specimens, and the strains were determined dividing the total stresses by AASHTO short-term modulus of elasticity. Figure 3 summarizes the results for these tests.

Figure 3. Test results for compression tests [*7*]



Material	Test No.	Diameter mm	Profile Type	Wall Area mm²/mm	Wall Moment of Inertia mm⁴/mm	Arc Length deg.	End Condition	Peak Load kN	Max. Strain %	
									In.	Out.
PE	A24F-1	600	Corrug.	7.8	5,020	15	P-F	19.0	3.9	3.9
	A24I-1	600	Corrug.	7.8	5,020	15	P-F	15.9	4.0	4.0
	B36E-1	900	Corrug.	9.94	6,075	35	P-F	39.2	5.3	NA
	B48A-1	1,200	Corrug.	10.5	8,470	45	F-F	29.2	2.4	3.2
	B48C-1	1,200	Corrug.	10.5	8,470	25	F-F	44.8	2.6	2.9
	E36D-1	900	Corrug.	14.2	12,310	15	P-F	62.0	2.4	2.7
	D48D-2	1,200	Honeycomb	10.7	7,830	15	P-F	31.6	2.4	2.7
PVC	C24C-1	600	Corrug.	9.3	975	7	P-F	59.1	1.7	1.8
	C24D-1	600	Corrug.	9.3	975	7	P-F	49.6	1.5	1.6
	C24E-1	600	Corrug.	9.3	975	7	P-F	58.4	1.7	1.8

Notes 1. 1 in. = 25.4 mm, 1 lb = 0.00445 kN
2. Inside compressive strain is maximum at the mid-height of the specimen, outside compressive strain is maximum at the specimen end.
3. F-P = fixed pinned end condition, F-F= fixed-fixed end condition.

Measured strains in the liner and valleys of PE specimens were generally less than predicted. For the PVC specimens, liner strains were approximately 80% of the valley strains. Conversely, in PE specimens, liner strains were only 40% of the valley strains. It was observed that PVC strains were much closer (within 10%) to what was originally predicted than PE values, except in the fixed-fixed test, where the difference was up to 25%. This is due to the uncertainty in the value of modulus of elasticity of PE specimens and the fact that the value is so low that the gauge can reinforce the specimen and modify its strain value. In PE specimens, the strains at the crest were generally less than predicted, except for the fixed-fixed case.

NCHRP Report 631

AASHTO first adopted plastic pipe design in bridge specifications in the 1980s but was largely based on corrugated metal pipe design procedure. This procedure focused on ring compression stresses and did not address bending or deflection. Recent research has provided additional approaches for pipe design. As shown by field experience, the deflection of plastic pipe can be high if construction procedures are not controlled. Therefore, deflection checks must be enforced during design and followed through during construction. Additional to the design issues, plastic pipes are made from raw materials with different properties, do not have standardized walls, and the manufacturing process is highly incidental on the final product. Thus, the tests performed on the final product are crucial to ensure the adequate performance of plastic pipes. The results of these tests should be requested by DOT before the acceptance of plastic pipes for every project.

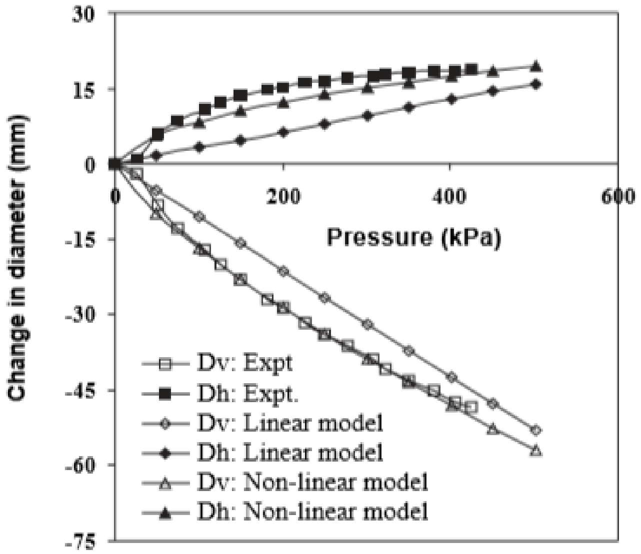
NCHRP Report 631 [*13*] is focused mainly on three primary areas:

- Pipe-soil interaction: studies on the complexities of the 3D behavior of profile wall pipe and the pipe-soil interaction of plastic pipe were carried out by soil cell studies and computer modeling.
- Design: the design work focused on findings related to the design of plastic pipe to carry loads it may be subjected to (earth, live, and water loads).
- QA/QC: investigations were carried out on plastic resins and pipes not embedded in the soil.

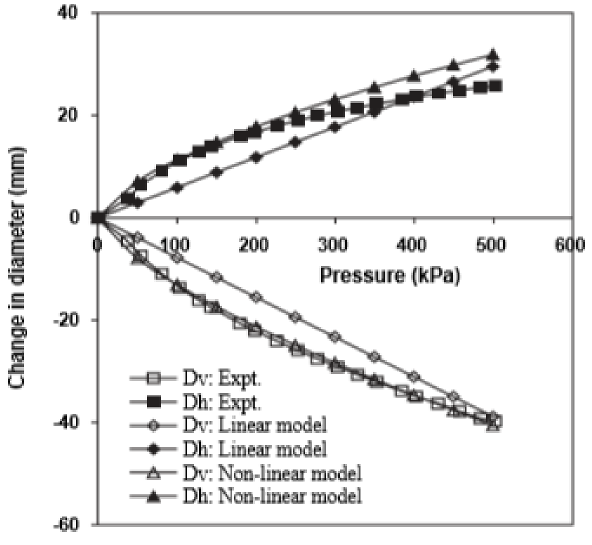
Studies of Pipe-Soil Interaction

The 2D behavior of plastic pipe was investigated through tests and computer modeling. The tests were performed on corrugated 24 in. inside diameter HDPE pipe and 24 in. inside diameter PVC pipe using a laboratory biaxial soil cell. The biaxial soil cell was 6.6 in. x 6.6 in. The pipes were embedded in poorly graded sand compacted to approximately 85% of maximum standard proctor density and were instrumented with strain gauges in the crest, web, liner, and valley of the pipe corrugation. Finite element models of the tests were also developed to measure the overall pipe behavior. Deflection data were compared with the model predictions and the results are presented in Figure 4. In general, the non-linear model captured the experimental results in both the horizontal and vertical directions. The linear model underestimates the deflection in both directions as pressure increases.

Figure 4. Comparison between measured deflection and computer model [*13*]



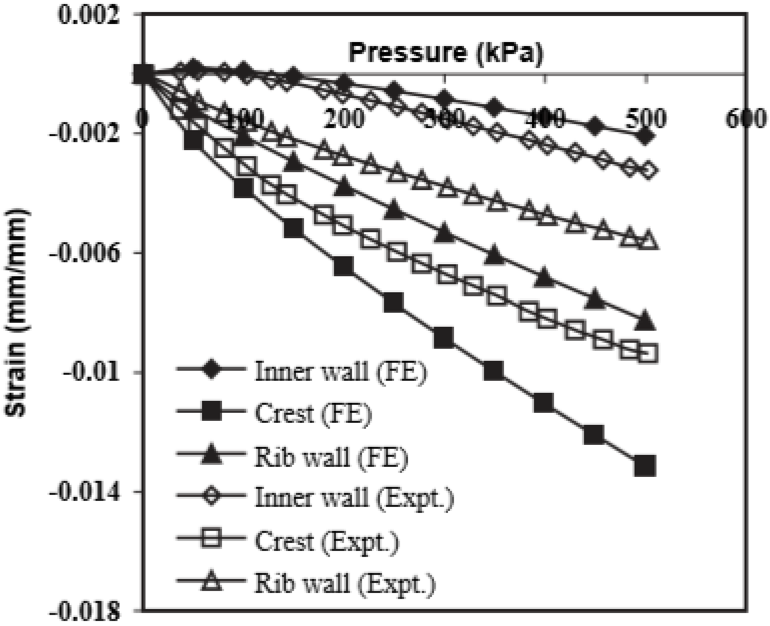
(a) HDPE pipe



(b) PVC pipe

The comparison of the measured deflection with the computer model was similar for all the locations of the strain gauges. Figure 5 shows the comparison between measured data and modeling prediction of the strain at the invert of the PVC pipe. The model effectively captures the behavior and response of the experimental data, even though it over predicts the strain at the crest and rib wall and slightly under predicts at the inner wall.

Figure 5. Comparison between measured deflection and computer model (PVC invert) [*13*]



Although high deflections and poor performance in actual installations occur despite good construction specifications, simplified design models and computer finite element model simulations reasonably estimate in-ground behaviors of buried thermoplastic pipe installations. Some of the findings from these experiments and models include the following:

- In general terms, plastic pipes provide good performance when installed according to good engineering practices.
- The simplified design techniques discussed below are adequate to predict the behavior of typical installation conditions.
- If unusual conditions are encountered and enough field control is used to ensure full compliance with the specifications, finite element models can be used to design plastic pipe installations.

- Proper construction and adequate QA/QC practices, as discussed later in the report, are crucial in the overall performance of plastic pipes.

Design

Tests were performed to investigate the behavior in compression and tension of PVC and HDPE resins used for plastic pipes and strain limit behavior of PVC and PE pipes. The PVC samples were both filled and unfilled resins. The results show the following:

- Previous assumptions relating to the compression behavior of PE pipes are appropriate. NCHRP Report 438 stated that a 4% compression strain limit is appropriate for PE, as this is where the stress-strain curves deviate to non-linear behavior.
- Tension strength is different for filled and unfilled resins; however, the compression strengths are approximately equal. This demonstrates that fillers disrupting the flow of tensile stress through the polymer can transfer compression stresses well, and this is similar to what occurs with aggregate in concrete.
- For PE and PVC resins, the modulus and strength are higher in compression than on tension if the Poisson effect is neglected.

The design methods for plastic pipe use the same limiting strength criteria to evaluate performance, such as compression thrust strain, combined bending and thrust strain, and general buckling.

The compression thrust strain derives from the soil, live, and external hydrostatic loads. The strain limits are set based on compression tests, which were based on strain at yield. This was valid with the assumption of linear behavior and the initial modulus of elasticity. Research performed in this report has shown that a fixed compressive strain limit is more appropriate and can be set as 4.1% for HDPE pipe and 2.6% for PVC.

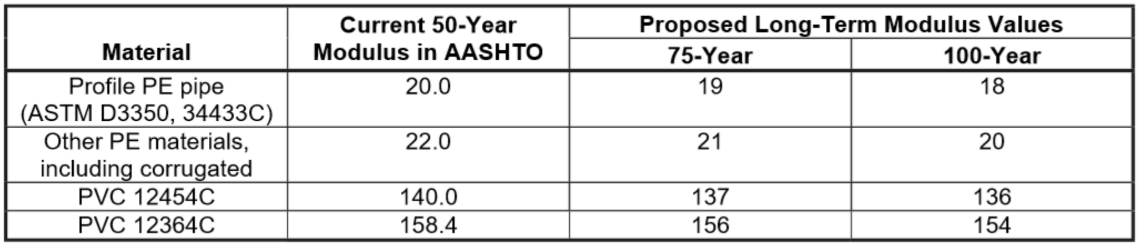
The combined strain results from adding the bending strain resulting from deflection to the thrust strain. Combined compression strain is allowed to be 50% larger than thrust strain alone. If properly installed plastic pipe, combined tension strain should be small or nonexistent. This project did not investigate tensile strain limits and thus recommends the criteria in the current AASHTO LRFD Bridge Specification.

Pipe walls must be sufficiently stiff to remain stable under compression loads. Currently, AASHTO evaluates buckling in plastic pipes using the Winkler model based on a spring-supported tube. Although Moore [*14*] shows that a model based on continuous pipe support better represents in-ground pipes and thus presents better predictions.

A summary of the findings in design is as follows:

- Soil load factors for buried flexible culverts are traditionally set to 2.0, while earth load factors for rigid culverts are set to 1.3. One of the major reasons for this may be that flexible culverts are subjected to high deflections if not properly installed. Although high deflections are still possible, plastic pipes can provide adequate performance based on deflections and service life performance according to AASHTO Standards even at great depths if properly installed. Two notable examples are 24-in. diameter pipes installed in Pennsylvania under approximately 100 ft. of fill [*15*] and a variety of PVC and HDPE pipes installed under 40 ft. of fill in Ohio [*16*]. To take advantage of this performance, the NCHRP report proposes a reduced soil load factor for plastic pipes to 1.3 but introduces an installation factor of 1.5 multiplied by the load factor, resulting in a total safety of 1.95 equal to the current specifications. If detailed construction controls are achieved, designers can reduce the installation factor to 1.0. No changes are proposed to the live load factors.
- No changes are proposed to the current AASHTO limit states. Strength limit states refer to wall area, buckling, and flexibility limit. The service limit state is mainly deflection.
- AASHTO specifications provide modulus of elasticity for initial and 50-year design periods. Because AASHTO now asks for a design life of 75 years for bridges, a similar standard should be applied for plastic pipes and the modulus of elasticity values should be revised. This report estimates the moduli of elasticity for longer design periods and they are shown in Figure 6.

Figure 6. Long-term design values for modulus of elasticity, ksi [*13*]



Material	Current 50-Year Modulus in AASHTO	Proposed Long-Term Modulus Values	
		75-Year	100-Year
Profile PE pipe (ASTM D3350, 34433C)	20.0	19	18
Other PE materials, including corrugated	22.0	21	20
PVC 12454C	140.0	137	136
PVC 12364C	158.4	156	154

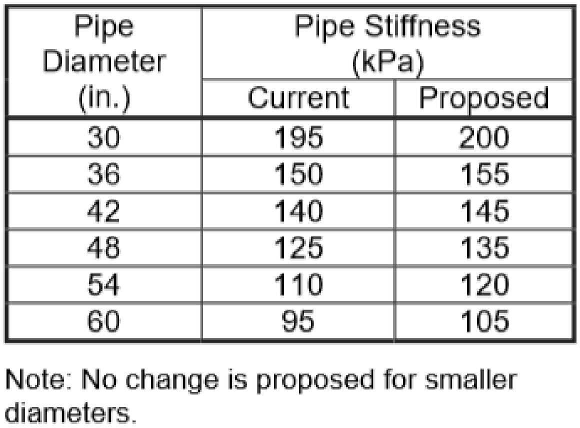
QA/QC

Deflection is the only service criterion for plastic pipe. AASHTO established a service limit of a 5% reduction in the vertical diameter. Although the actual service limit of plastic pipe will be variable, the AASHTO limit must be taken as reference. When evaluating an installation and a deflection greater than 5% is encountered, the actual service deflection limit can be calculated and used instead.

Regarding resin materials, plastic pipes must meet the product specifications to guarantee an adequate service life following the manufacturer's guidelines. This requires that the product is made from suitable raw materials and that the finished products have the required geometry, materials, strength, and durability. The primary reference is the AASHTO M294 Standard for PE pipes.

The finished product is tested to evaluate strength, stiffness, and durability. Current tests include dimensions, pipe stiffness, flattening (strength), environmental stress cracking, and brittleness (impact). For PE pipes, the parallel plate test must be conducted until 20% vertical deflection is achieved in the pipe with a constant crosshead speed of 0.5 in./min with no loss of load, cracking, or local buckling. The test duration is long for large diameter pipes. Because the strain rate decreases for large diameter pipes, the effective modulus elasticity of the pipe also decreases with slower strain rates. Thus, the test evaluates each size pipe at a different modulus, which is not desirable. Therefore, it is suggested to increase the test speed in the parallel plate test in plastic pipes to 2% of the nominal inside diameter/minute. This change will provide an approximately same strain rate for pipes larger than 24 in. and will reduce the testing time. Because the apparent stiffness will increase if the strain rate is also increased, Figure 7 provides an increased minimum stiffness using higher test rates to preserve the same pipe stiffness as is currently required.

Figure 7. Recommended modification to pipe stiffness to account for higher strain rate [*13*]



Pipe Diameter (in.)	Pipe Stiffness (kPa)	
	Current	Proposed
30	195	200
36	150	155
42	140	145
48	125	135
54	110	120
60	95	105

Note: No change is proposed for smaller diameters.

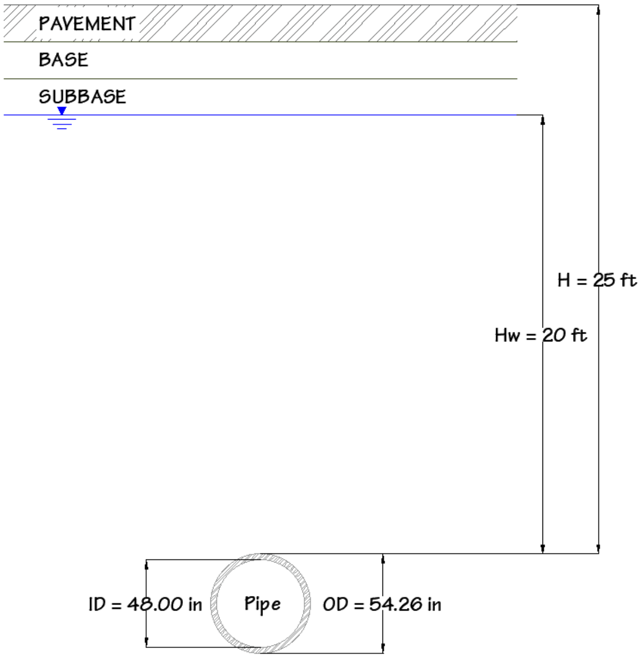
For PVC pipes, the reference standard is AASHTO M304 [*17*]. Similar to PE pipes, important parameters for PVC are strength, stiffness, processing, and durability. The current tests for PVC include dimensions; pipe stiffness; flattening (splitting, cracking, rib separation); impact; and acetone immersion.

Stiffness standards are the same for PE and PVC pipes. However, the flattening test is significantly different. PVC testing for flattening requires that the pipe may be able to withstand loads to 60% vertical deflection without cracking, splitting, breaking, or separation of the seams, but the load on the top of the pipe can decrease. Thus, the flattening test for PVC evaluates material strength more than pipe strength.

AASHTO LRFD Bridge Design Specifications, 8th Edition

Chapter 12 of the *AASHTO LRFD Bridge Design Specifications* [*18*] was reviewed because it addresses "Buried Structures and Tunnel Liners." This section of the specification addresses the types of soils and material properties used for bedding and backfilling of the trench; general design features (loads, settlements, and uplifting forces); and trench and cover minimum dimensions among other important items. A summary of the most important properties discussed in this section is presented in Table 8. The design process according to Section 12.12 of the AASHTO specification was reviewed for a 48-in. pipe to determine the sensitivity of input parameters on performance. The parameters for design are a cover height of 25 ft., moist unit weight of soil is 120 pcf, the water level is 5 ft. below the ground surface, and the saturated unit weight of soil is 130 pcf, soil type SN (GW, GP, SW or SP according to ASTM D2487) compacted to 95% of maximum dry density according to AASHTO T 99. Figure 8 shows a schematic of the scenario considered for design.

Figure 8. Pipe considered for design example



The allowable deflection is 5% of the internal diameter according to *NCHRP Report 631* Appendix E.3 and *AASHTO LRFD Bridge Design Specifications*, Section 12.15.4. All of the parameters and formulas for calculation were obtained from the AASHTO specification. The allowable deflection, in this case, is 2.40 in. The calculated total deflection for this design problem is equal to ~1.4 in. using the initial modulus of pipe material, which is lower than the allowable and thus deemed acceptable. Because the water table is above the pipe, the hydrostatic pressure must be taken into account to calculate the soil prism pressure above the pipe (P_{sp}) and the buoyancy force in the pipe. The weight of the pipe and the soil above the pipe must counteract the uplift forces due to water pressures below the pipe. The critical backfilling height to overcome the uplift forces was determined to be ~10.0 ft., which is lower than the considered backfill. The buoyancy force is determined to be less than the sum of the weight of the pipe and the soil on top of it. Table 8 and Table 9 summarize the calculations and results.

The design process in Table 8 suggests that the predicted deflections are less than the allowable deflections using the initial corrugated PE pipe modulus. Figure 9 shows the initial and long-term (75 years) moduli for different pipe materials. If the pipe modulus is reduced to the long-term value of 21 ksi, the deflection increases to ~3.5 in., which is unsatisfactory. Reducing the PE pipe modulus over time suggests that long-term deflections can approach values greater than the allowable deflections. This comparison corroborates field observations by Abolmaali et al. [*19*] that the root failure mechanism of HDPE pipes is excessive deformation. The same design process can be performed for other plastic pipes. For PVC pipes, the modulus of pipe material changes to 400 ksi and 137 ksi for initial and long-term conditions, respectively. The shape profile also varies to the PVC. Accounting for these differences, the PVC deflection is predicted as ~0.80 in. and ~1.1 in. for initial and long-term conditions, respectively. Compared to PE pipes, PVC pipes allow less deflection. The same process can be carried out for PP pipes. The modulus for this material pipe changes to 175 ksi for initial conditions and the corresponding deflection is predicted as ~1.0 in. For the long-term condition, the modulus decreases to 28 ksi, and the deflection is predicted as ~2.5 in., slightly higher than the 5% allowable deflection, which would correspond to 2.40 in. for this pipe diameter and thus is still unacceptable. This design process indicates that the modulus of the pipe is a critical parameter for predicting initial and long-term deflections. Excessive deformation can still occur in the field, as indicated in Abolmaali et al. [*19*]. These field observations indicate that there is still yet uncertainty in the long-term performance of plastics that specifically involves understanding how the modulus changes with time and loading history.

Table 8. Total deflection parameters and calculations

Parameter	Section		Value	Unit
Bedding coefficient	—	K_B	0.10	—
Deflection lag factor	—	D_L	1.50	—
Soil prism pressure (springline)	12.12.3.7	P_{sp}	14.61	psi
Live load coefficient	12.12.3.5-5	C_L	0.80	—
Live load pressure	3.6.1.2.6	P_L	0.08	psi
Outside diameter	Figure C12.12.2.2-1	D_o	54.26	in.
Modulus of pipe material	Table 12.12.3.3-1	E_p	110 (initial) 21 (long)	ksi ksi
Moment of inertia	—	I_p	0.65	in.^{4}/in.
Radius from center to centroid	Figure C12.12.2.2-1	R	25.27	in.
Secant constrained soil modulus	Table 12.12.3.5-1	M_s	3.208	ksi
Service compressive strain	12.12.3.10.1c	ε_{sc}	0.0154	—
Diameter to centroid	Figure C12.12.2.2-1	D	50.54	in.
Wall thickness	—	t	3.13	in.
Total deflection	—	Δ_t	1.38 (initial)	in.
Allowable deflection (5%*D_i)	NCHRP Report 631	Δ_a	2.40	in.
Service thrust	12.12.3.5-2	T_s	516.04	lb/in.
Thrust variation around circ. factor	springline (1.0), crown (0.6)	K_2	1.00	—
Vertical arching factor	12.12.3.5-3	VAF	0.71	—
Hoop stiffness factor	12.12.3.5-4	S_H	1.50	—
Resistance factor for soil stiffness	Table 12.5.5-1	ϕ_s	0.90	—
Secant constrained soil modulus	Table 12.12.3.5-1	M_s	3.208	ksi
Radius from center to centroid	Figure C12.12.2.2-1	R	25.27	in.
Modulus of pipe material	Table 12.12.3.3-1	E_p	110 (initial) 21 (long)	ksi
Gross area of pipe wall	12.12.3.5-4	A_g	0.44	in.^{2}/in.
Soil prism pressure (springline)	12.12.3.7	P_{sp}	14.61	psi
Depth of fill over top of pipe	—	H	25	ft.
Outside diameter	Figure C12.12.2.2-1	D_o	54.26	in.
Unit weight of soil	—	γ_s	120	pcf
Saturated unit weight of soil	—	γ_{sat}	130	pcf

Live load vertical crown pressure	3.6.1.2.6b-7	P_L	0.01	ksf
			0.08	psi
Live load applied at surface	3.6.1.2.6b-7	P	16.00	kip
Dynamic load allowance	3.6.2.2-1	IM	100%	—
Minimum depth of earth cover	3.6.2.2-1	D_E, H	25.00	ft.
Multiple presence factor	Table 3.6.1.1.2-1	m	1.20	1
Live load vertical crown pressure	3.6.1.2.6a-1	A_{LL}	1,597.62	ft.^{2}
Wheel interaction depth transversal	3.6.1.2.6b-1	$H_{int\text{-}t}$	3.56	ft.
Wheel spacing	3.6.1.2.6b-1	s_w	6	ft.
Tire patch width	3.6.1.2.6b-1	w_t	20	in.
Diameter to centroid	Figure C12.12.2.2-1	D_i	48	in.
Live load distribution factor	Table 3.6.1.2.6a-1	$LLDF$	1.15	—
Live load patch width at depth *H*	3.6.1.2.6b-2 / 3.6.1.2.6b-3	W_W	36.66	ft.
Live load coefficient	12.12.3.5-5	C_L	0.80	—
Live load patch length at depth *H*	3.6.1.2.6b-5 / 3.6.1.2.6b-6	L_W	43.58	ft.
Axel spacing	3.6.1.2.6b-4	s_a	14	ft.
Tire patch length	3.6.1.2.6b-4	l_t	10	in.
Live load distribution factor	Table 3.6.1.2.6a-1	$LLDF$	1.15	—
Axle interaction depth parallel	3.6.1.2.6b-4	$H_{int\text{-}p}$	11.45	ft.
Factor	12.12.3.5-6	F_1	1.00	—
Factor	12.12.3.5-7	F_{min}	1.00	—
Factor	12.12.3.5-8	F_2	0.50	—
Hydrostatic water pressure (springline)	12.12.3.8-1	P_W	8.67	psi
Unit weight of water	12.12.3.8-1	γ_w	62.4	pcf
Uncertainty factor in groundwater depth	12.12.3.8-1	K_{wa}	1.00	—
Depth of water level above springline	12.12.3.8-1	H_w	20.0	ft.
Service compressive strain	12.12.3.10.1c	ε_{sc}	0.0154	—
Service thrust	12.12.3.5-2	T_s	516.04	lb/in.
Effective area of pipe wall	—	A_{ff}	0.30	in.^{2}/in.
Modulus of pipe material	Table 12.12.3.3-1	E_p	110 (initial) 21 (long)	ksi

Table 9. Buoyancy parameters and calculations

Parameter	Section		Value	Unit
Area of pipe	—	A_{pipe}	3.49	ft.^{2}
Density of pipe	—	ρ_{PE}	58.63	lb/ft.^{3}
Weight of pipe	—	W_{pipe}	204.70	lb/ft.
Unit weight of soil	—	γ_s	120	pcf
Saturated unit weight of soil	—	γ_{sat}	130	pcf
Unit weight of water	12.12.3.8-1	γ_w	62.4	pcf
Depth of water level above springline	12.12.3.8-1	H_w	20	ft.
Outside diameter	Figure C12.12.2.2-1	D_o	54.26	in.
			4.52	ft.
Buoyancy force	—	U	1,002.01	lb/ft.
		U-W_{pipe}	797.31	lb/ft.
Critical height above pipe	—	$H_{crit} \geq$	9.93	ft.
Area of pipe	—	A_{pipe}	3.49	ft.^{2}
Density of pipe	—	ρ_{PE}	58.63	lb/ft.^{3}
Weight of pipe	—	W_{pipe}	204.70	lb/ft.
Weight of soil above pipe	—	W_{soil}	8,974.59	lb/ft.
Unit weight of soil	—	γ_s	120	pcf
Saturated unit weight of soil	—	γ_{sat}	130	pcf
Unit weight of water	12.12.3.8-1	γ_w	62.4	pcf
Depth of fill over top of pipe	—	H	25	ft.
Depth of water level above springline	12.12.3.8-1	H_w	20	ft.
Outside diameter	Figure C12.12.2.2-1	D_o	54.26	in.
			4.52	ft.
Buoyancy force	—	U	1,002.01	lb/ft.
		$U<W_{soil}+W_{pipe}$?	Ok	—

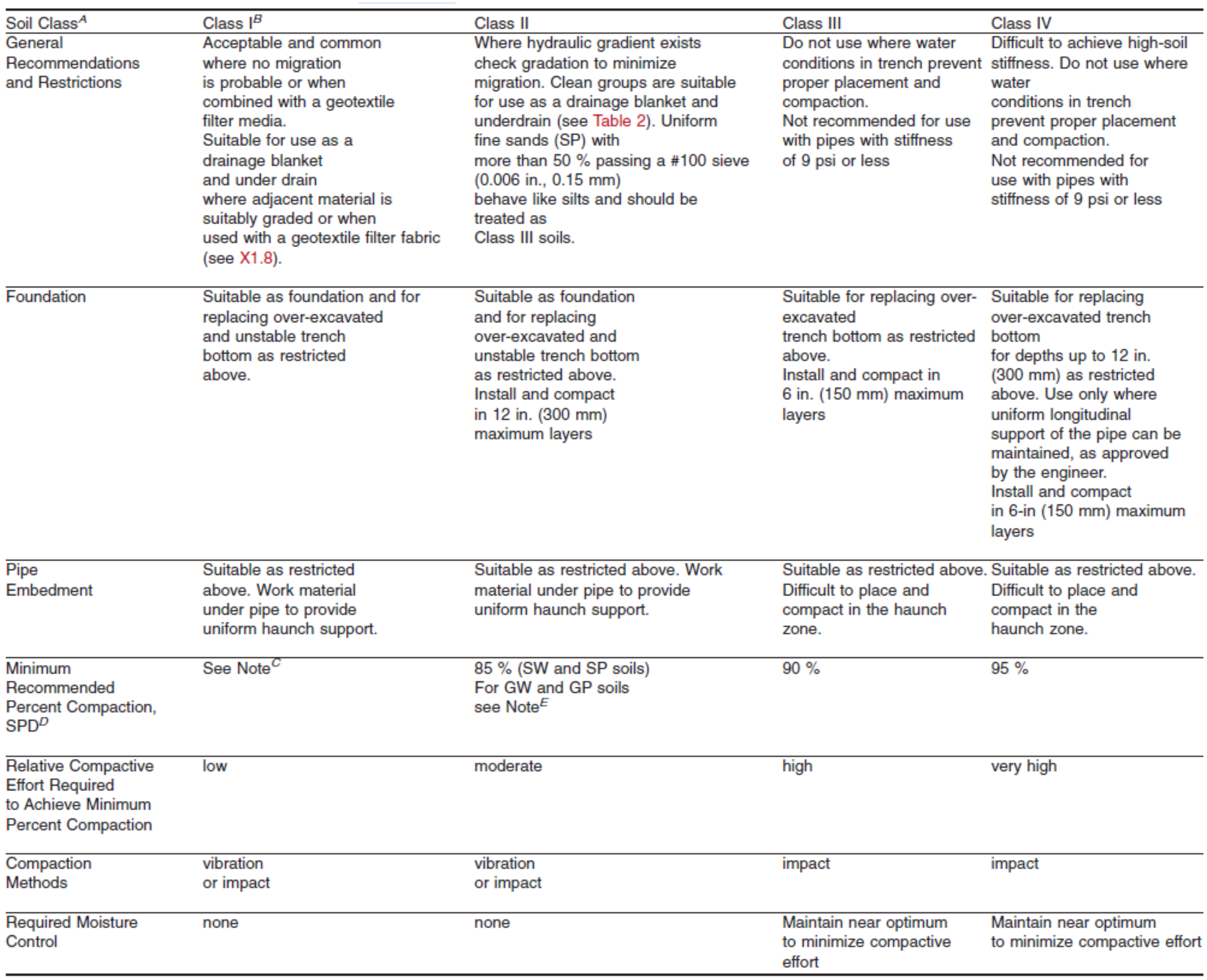
Figure 9. Mechanical properties of thermoplastic pipe [*18*]

Type of Pipe	Minimum Cell Class	Service Long-Term Tension Strain Limit, ε_{yt} (%)	Factored Compr. Strain Limit, ε_{yc} (%)	Initial		50-yr		75-yr	
				F_u min (ksi)	E min (ksi)	F_u min (ksi)	E min (ksi)	F_u min (ksi)	E min (ksi)
Solid Wall PE Pipe – ASTM F714	ASTM D3350, 335434C	5.0	4.1	3.0	110.0	1.44	22	1.40	21
Corrugated PE Pipe – AASHTO M 294	ASTM D3350, 435400C	5.0	4.1	3.0	110.0	0.90	22	0.90	21
Profile PE Pipe – ASTM F894	ASTM D3350, 334433C	5.0	4.1	3.0	80.0	1.12	20	1.10	19
	ASTM D3350, 335434C	5.0	4.1	3.0	110.0	1.44	22	1.40	21
Solid Wall PVC Pipe – AASHTO M 278, ASTM F679	ASTM D1784, 12454C	5.0	2.6	7.0	400.0	3.70	140	3.60	137
	ASTM D1784, 12364C	3.5	2.6	6.0	440.0	2.60	158	2.50	156
Profile PVC Pipe – AASHTO M 304	ASTM D1784, 12454C	5.0	2.6	7.0	400.0	3.70	140	3.60	137
	ASTM D1784, 12364C	3.5	2.6	6.0	440.0	2.60	158	2.50	156
Corrugated PP Pipe AASHTO M 330	Requirements in M 330	2.5	3.7	3.5	175	1.0	29	1.0	28

ASTM D2321-18

The standard ASTM D2321-18 Standard Practice for Underground Installation of Thermoplastic Pipe for Sewers and other Gravity-Flow Applications [*20*] provides a guideline regarding the type of soil to be used for embedment and backfill purposes. The soil used for these purposes must contain material passing the 1 ½-in. sieve and its water content must be kept ± 3% of the optimal water content. It is specified that pipes must not be laid in standing or running water. A minimum of 4 in. must be provided for the trench bottom and must be firm, stable, and uniform. If rock or unyielding materials (hardpan, shale, cobbles, and boulders) are encountered, these must be removed and a cushion of at least 6 in. must be placed below the pipe. The minimum trench width is specified in Table 12 under Task 4. General recommendations, compaction requirements, and lift widths, among other relevant information, are summarized in Figure 10. The recommendations the standard provides are similar to what DOTD specifications require for trench width, trench bottom, soil materials to be used, minimum cover, compaction requirements, and other important considerations for the adequate performance of the pipe. As it is stated in the ASTM standard, these recommendations and values can be modified by the engineer according to the specific needs of each project.

Figure 10. Recommendations for installation and use of soils and aggregates for foundation and pipe-zone embedment [*20*]



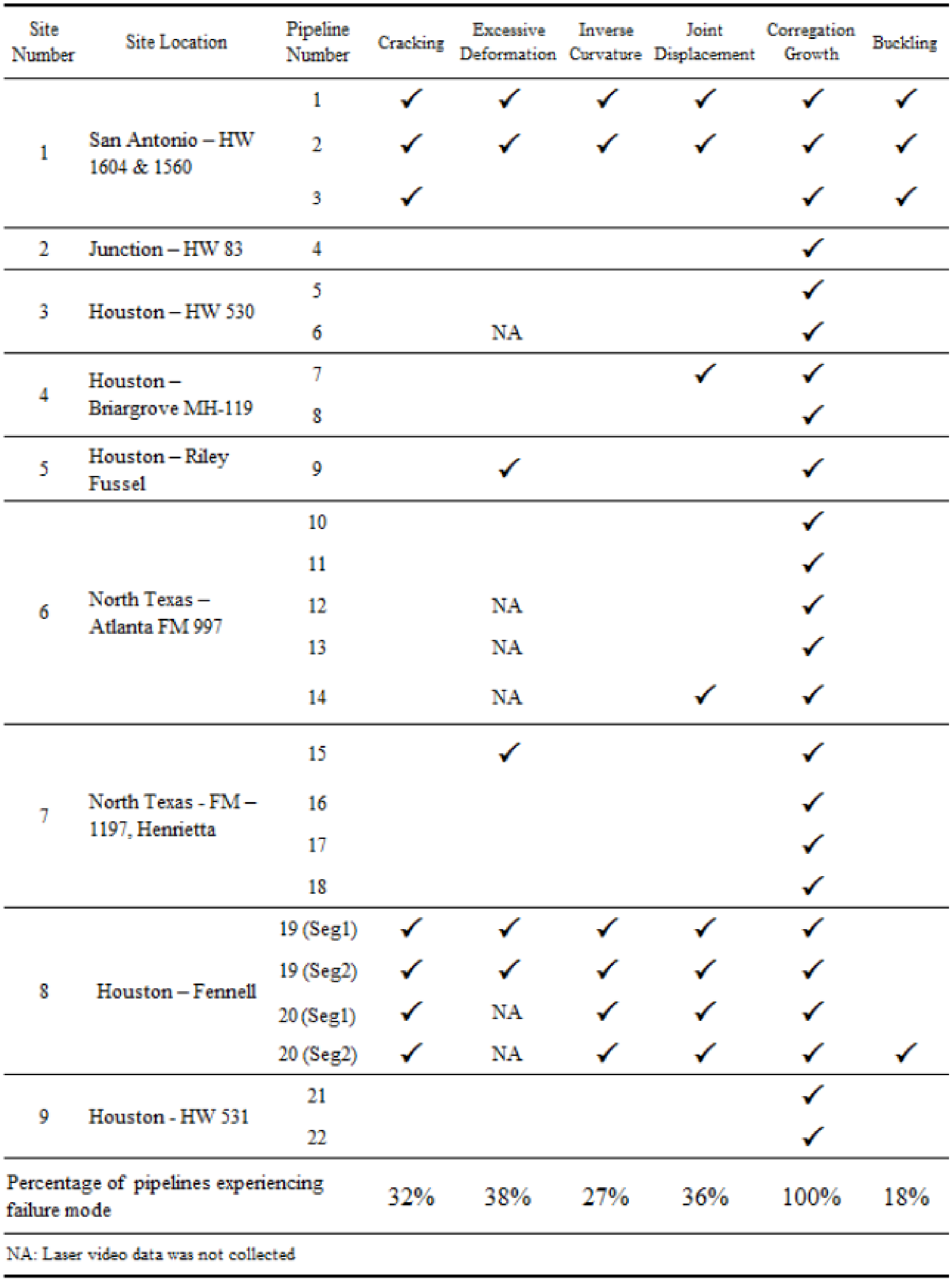
Soil Class[A]	Class I[B]	Class II	Class III	Class IV
General Recommendations and Restrictions	Acceptable and common where no migration is probable or when combined with a geotextile filter media. Suitable for use as a drainage blanket and under drain where adjacent material is suitably graded or when used with a geotextile filter fabric (see X1.8).	Where hydraulic gradient exists check gradation to minimize migration. Clean groups are suitable for use as a drainage blanket and underdrain (see Table 2). Uniform fine sands (SP) with more than 50 % passing a #100 sieve (0.006 in., 0.15 mm) behave like silts and should be treated as Class III soils.	Do not use where water conditions in trench prevent proper placement and compaction. Not recommended for use with pipes with stiffness of 9 psi or less	Difficult to achieve high-soil stiffness. Do not use where water conditions in trench prevent proper placement and compaction. Not recommended for use with pipes with stiffness of 9 psi or less
Foundation	Suitable as foundation and for replacing over-excavated and unstable trench bottom as restricted above.	Suitable as foundation and for replacing over-excavated and unstable trench bottom as restricted above. Install and compact in 12 in. (300 mm) maximum layers	Suitable for replacing over-excavated trench bottom as restricted above. Install and compact in 6 in. (150 mm) maximum layers	Suitable for replacing over-excavated trench bottom for depths up to 12 in. (300 mm) as restricted above. Use only where uniform longitudinal support of the pipe can be maintained, as approved by the engineer. Install and compact in 6-in (150 mm) maximum layers
Pipe Embedment	Suitable as restricted above. Work material under pipe to provide uniform haunch support.	Suitable as restricted above. Work material under pipe to provide uniform haunch support.	Suitable as restricted above. Difficult to place and compact in the haunch zone.	Suitable as restricted above. Difficult to place and compact in the haunch zone.
Minimum Recommended Percent Compaction, SPD[D]	See Note[C]	85 % (SW and SP soils) For GW and GP soils see Note[E]	90 %	95 %
Relative Compactive Effort Required to Achieve Minimum Percent Compaction	low	moderate	high	very high
Compaction Methods	vibration or impact	vibration or impact	impact	impact
Required Moisture Control	none	none	Maintain near optimum to minimize compactive effort	Maintain near optimum to minimize compactive effort

Evaluation of the Structural Performance of HDPE Pipelines

The report *Evaluation of HDPE Pipelines Structural Performance* performed by Abolmaali et al. [*19*] presents a comprehensive evaluation of the performance of 191 HDPE pipelines installed in 10 different states. The evaluations were performed in Texas, North Carolina, Virginia, Minnesota, Kansas, Missouri, California, Utah, Michigan, and Florida. The study analyzes over 31,000 ft. of HDPE pipeline sections. The type of failure was detected with video inspections using a high-intensity lighting inspection camera. The deformations were quantified using a pipeline laser profiling unit in which a ring of laser light, perpendicular to the longitudinal axis of the pipe, is projected on the inside of the pipe and later processed in special software to determine the change in the pipe's diameter in the vertical or horizontal direction. Additionally, as the maximum deformation can occur diagonally, how oval or out of round the pipe is after deformation was also determined. This study refers to this measure as ovality. The failure modes detected throughout the investigations are excessive deformation, joint displacement, cracking/fracture, inverse curvature, buckling, and corrugation growth. More than 60% of the pipelines suffered excessive deformation and 100% suffered corrugation growth. All the other failure modes were encountered in 15 to 40% of the HDPE pipelines. These results give evidence to the need to determine the long-term performance properties of HDPE and other thermoplastic pipes and investigate the cause of such failure modes.

In Houston, more than 1,300 ft. of pipeline sections were inspected. Figure 11 lists the types of failures observed in Houston and other locations in Texas. Figure 12 summarizes the deformation values of different pipelines in Texas. Finally, Figure 13 shows an image from the laser-profiling unit and Figure 14 shows the interior of a pipe in Houston Site 8. Unfortunately, the report does not provide guidance on why the excessive deformation mechanism, among the other failure modes, occurred given the design process predicted less than the 5% limit. They recommended that more knowledge is needed on the long-term properties of HDPE pipes subjected to diverse service loads.

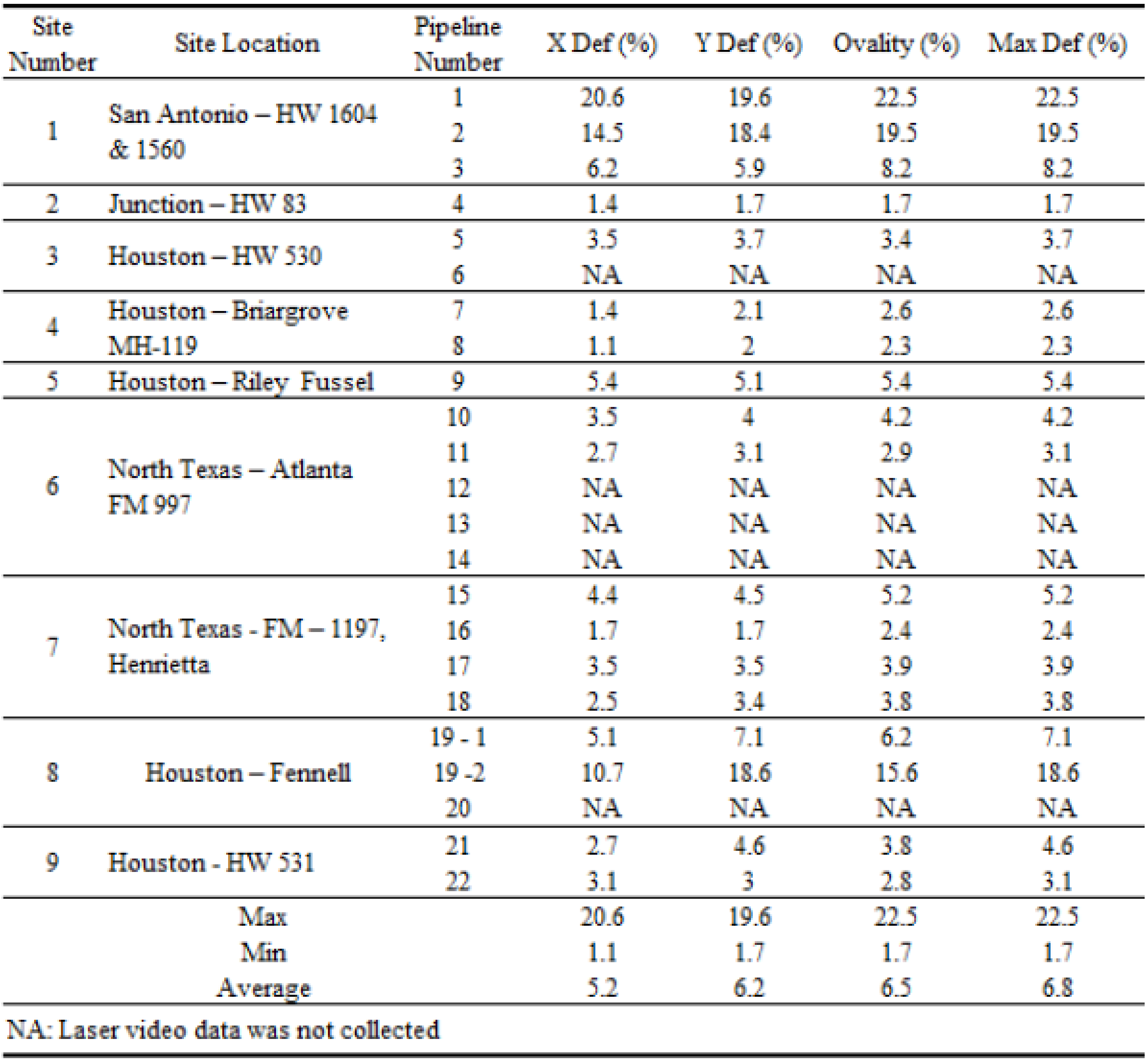
Figure 11. Different observed damage in Houston and other locations in Texas [*19*]



Site Number	Site Location	Pipeline Number	Cracking	Excessive Deformation	Inverse Curvature	Joint Displacement	Corregation Growth	Buckling
1	San Antonio – HW 1604 & 1560	1	✓	✓	✓	✓	✓	✓
		2	✓	✓	✓	✓	✓	✓
		3	✓				✓	✓
2	Junction – HW 83	4					✓	
3	Houston – HW 530	5					✓	
		6		NA			✓	
4	Houston – Briargrove MH-119	7				✓	✓	
		8					✓	
5	Houston – Riley Fussel	9		✓			✓	
6	North Texas – Atlanta FM 997	10					✓	
		11					✓	
		12		NA			✓	
		13		NA			✓	
		14		NA		✓	✓	
7	North Texas - FM – 1197, Henrietta	15		✓			✓	
		16					✓	
		17					✓	
		18					✓	
8	Houston – Fennell	19 (Seg1)	✓	✓	✓	✓	✓	
		19 (Seg2)	✓	✓	✓	✓	✓	
		20 (Seg1)	✓	NA	✓	✓	✓	
		20 (Seg2)	✓	NA	✓	✓	✓	✓
9	Houston - HW 531	21					✓	
		22					✓	
Percentage of pipelines experiencing failure mode			32%	38%	27%	36%	100%	18%

NA: Laser video data was not collected

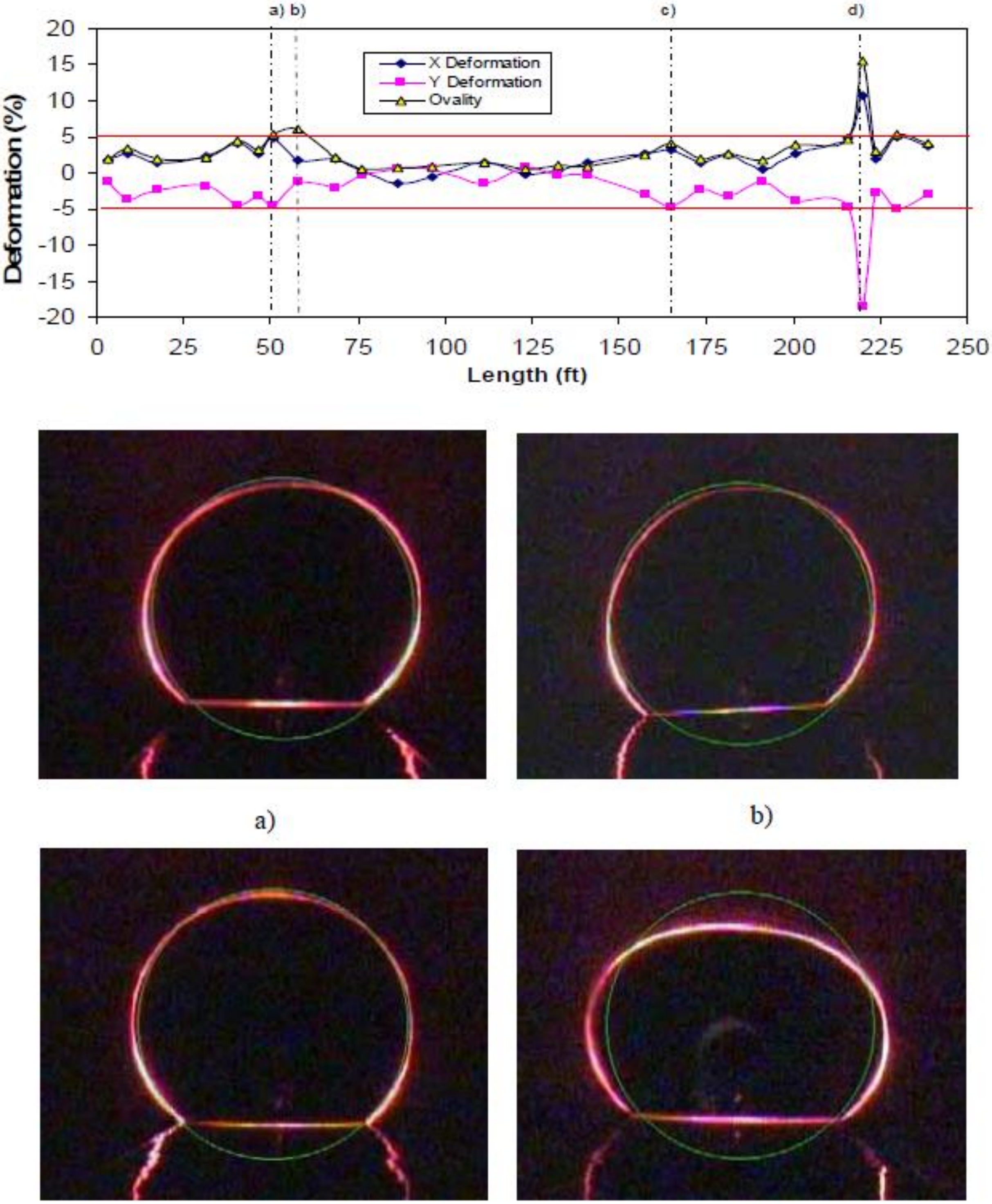
Figure 12. Summary of deformation of pipelines [*19*]



Site Number	Site Location	Pipeline Number	X Def (%)	Y Def (%)	Ovality (%)	Max Def (%)
1	San Antonio – HW 1604 & 1560	1	20.6	19.6	22.5	22.5
		2	14.5	18.4	19.5	19.5
		3	6.2	5.9	8.2	8.2
2	Junction – HW 83	4	1.4	1.7	1.7	1.7
3	Houston – HW 530	5	3.5	3.7	3.4	3.7
		6	NA	NA	NA	NA
4	Houston – Briargrove MH-119	7	1.4	2.1	2.6	2.6
		8	1.1	2	2.3	2.3
5	Houston – Riley Fussel	9	5.4	5.1	5.4	5.4
6	North Texas – Atlanta FM 997	10	3.5	4	4.2	4.2
		11	2.7	3.1	2.9	3.1
		12	NA	NA	NA	NA
		13	NA	NA	NA	NA
		14	NA	NA	NA	NA
7	North Texas - FM – 1197, Henrietta	15	4.4	4.5	5.2	5.2
		16	1.7	1.7	2.4	2.4
		17	3.5	3.5	3.9	3.9
		18	2.5	3.4	3.8	3.8
8	Houston – Fennell	19 - 1	5.1	7.1	6.2	7.1
		19 -2	10.7	18.6	15.6	18.6
		20	NA	NA	NA	NA
9	Houston - HW 531	21	2.7	4.6	3.8	4.6
		22	3.1	3	2.8	3.1
	Max		20.6	19.6	22.5	22.5
	Min		1.1	1.7	1.7	1.7
	Average		5.2	6.2	6.5	6.8

NA: Laser video data was not collected

Figure 13. Laser profiling unit ring for Houston, Site 8 [*19*]



a)

b)

b)

d)

Figure 14. Joint displacement, cracking/fracture, and inverse curvature failures for pipeline in Houston, Site 8 [*19*]

NCHRP Report 473

Report 473 was reviewed, but it was determined that it is not relevant to the scope of this report as it focuses on specifications for large-span culverts.

Task 3. Other State DOT's Practices

Florida

Florida DOT approves use of polypropylene pipe [*21*]. The Florida Department of Transportation (FDOT) has approved the use of high performance (HP) polypropylene (PP) pipe in 12-in. through 60-in. diameters for 100-year design service life applications under FDOT's 2014 *Standard Specifications for Road and Bridge Construction*, Section 948-7. According to FDOT documents, polypropylene pipe has passed the needed testing to be accepted for a 100-year side drain, cross drain, and storm sewer applications. Until project plans and specifications reflect this update, PP pipe may be selected by the contractor for any project where high-density polyethylene (HDPE) pipe is allowed.

To determine the expected service life of high performance (HP) pipe, FDOT adopted a test protocol specification that projected long-term buried stress and environmental conditions using stress crack resistance and oxidation resistance testing to predict the long-term performance of the plastic pipe.

Class I (50-year design life) HP polypropylene pipe (PP) used for storm drains, side drains, and cross drains must meet the requirements of AASHTO M 330 and ASTM F2881 [22]. Class II (100-year design life) PP life has to meet all requirements of Class I PP and the additional requirements established in Table 10. These test requirements verify a 100-year crack-free and anti-oxidant service life at service temperature (25ºC), according to FDOT's state specifications engineer. FDOT has similar testing requirements for Class II (100-year design life) HDPE pipes.

Table 10. Additional requirements for class II (100-year design life) PP [22]

Stress Crack Resistance			
Pipe Location	**Test Method**	**Test Conditions**	**Requirement**
Pipe Liner	FM 5-572, Procedure A	10% Igepal solution at 50°C and 600 psi applied stress, 5 replicates	Average failure time of the pipe liner shall be ≥100 hours, no single value shall be less than 71 hours.(1)
Oxidation Resistance			
Pipe Location	**Test Method**	**Test Conditions**	**Requirement**
Pipe Liner and/or Crown(2)	OIT Test (ASTM D3895)	2 replicates (to determine initial OIT value) on the as manufactured (not incubated) pipe.	25.0 minutes, minimum
Pipe Liner and/or Crown(2)	Incubation test FM 5-574 and OIT test (ASTM D3895)	Three samples for incubation of 264 days at 85°C(3). One OIT test per each sample	Average of 3.0 minutes(4) (no values shall be less than 2.0 minutes)
Pipe Liner and/or Crown(2)	MI test (ASTM D1238 at 230ºC/2.16Kg)	2 replicates on the as manufactured (not incubated) pipe.	< 1.5 g/10 minutes
Pipe Liner and/or Crown(2)	Incubation test FM 5-574 and MI test (ASTM D1238 at 230°C/2.16Kg)	2 replicates on the three aged sampled after incubation of 264 days at 85°C(3)	MI Retained Value(4)(5)(6) shall be greater than 80% and less than 120%.

Note: FM = Florida Method of Test.

(1)If due to sample size this test cannot be completed on the liner, then testing shall be conducted on a molded plaque sample. Samples can be removed if the test time exceeds 100 hours without failure.

[2] OIT and MI tests on the crown are required when resin used in the corrugation is different from that of the liner.

[3] The incubation temperature and duration can also be 192 days at 90°C or 140 days at 95°C.

[4] The tests for incubated and "as-manufactured" pipe samples shall be performed by the same lab, same operator, the same testing device, and on the same day.

[5] Within each replicate set of tests, the discrepancy range shall be within 9%. If an out-of-range discrepancy occurs, repeat the two MI tests on the same pipe sample. If insufficient material is available, a repeat of one test is acceptable.

[6] The MI retained value is determined using the average MI value of the incubated sample divided by the average MI value of the as-manufactured pipe sample.

Texas

Texas DOT, in the *Standard Specifications for Construction and Maintenance of Highways, Streets and Bridges* [*23*] determines that plastic pipes (PVC, HDPE, and PP) are suitable as new pipe culverts under Phase I restrictions and the Statewide Special Specification 4122. Phase I restrictions are listed as follows:

- Roadways with current ADT less than 2,000 per lane.
- Inside pipe diameters no greater than 36 in.
- Multiple pipe installations will be limited to a maximum of two adjacent pipes.
- Fill heights over pipe from 2 ft. to 12 ft. Minimum fill height for private driveways may be reduced to 1 ft.
- Installations for cross-drainage or side-drainage culverts. The purpose of this restriction is to allow post-construction inspection and evaluation of the pipe installation without having to enter manholes or other closed systems. Closed storm sewer systems are specifically disallowed under this restriction.

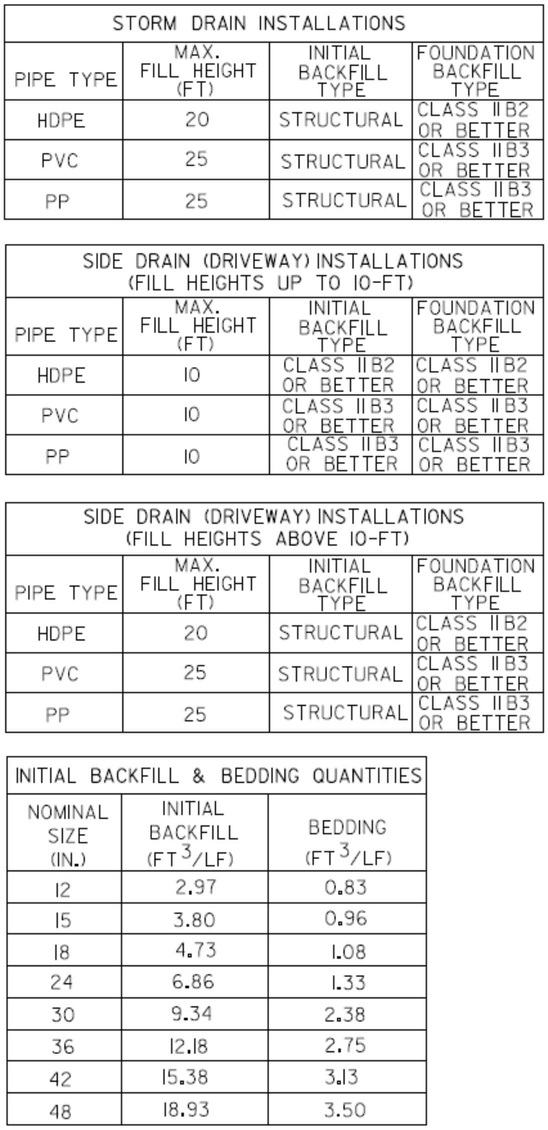
Georgia

Georgia Department of Transportation, through the *Supplemental Specifications Construction of Transportation Systems* [*24*], includes plastic pipes (HDPE, PP, and PVC) as usable materials for storm drain pipe, pipe-arch and elliptical culverts, side drain pipe flared end sections, and tapered pipe inlets. It also provides information regarding materials to be used, construction requirements, construction, quality acceptance, requirements for plastic pipes, among other items. The materials to be used are foundation backfill type I, defined as mixtures of materials consisting of hard, durable particles of sand or stone, mixed with silt, clay and/or humus, or foundation backfill type II, defined as crushed stone, gravel, or synthetic aggregate as per Supplemental Specification Section 812-Backfill Materials [*25*] and Section 800-Coarse Aggregate [*26*]. Special care must be taken when installing pipes outside the roadbed. The cover height must be up to 10 ft. If HDPE pipes are used, the material must be Class II B2 soil (medium to well-graded sandy silts) or better as per Section 810-Roadway Materials [*27*]. If PVC or PE pipes are used, the material must be

Class II B3 soil or better (medium to well-graded clays with some mica). Temporary drainage must be provided during construction to allow proper pipe flow and maintain drainage. During construction, the engineer must check the vertical and horizontal alignment of the pipe by checking for sagging, faulting, and invert heaving along the crown, invert, and sides of the pipe. The installation of thermoplastic pipe must be achieved according to ASTM D 2321 [*20*] guidelines. Post-installation inspection must be done after at least 8 ft. of compacted backfill or total compacted backfill has been achieved. Inspection must be carried out by low barrel distortion video equipment with laser profile technology. Manual post-installation inspection is allowed for 48 in. diameter or greater pipes. During the inspection, the engineer must check for joints, cracks, buckling, and deflection failures. If pipe deflection exceeds 5% of the nominal diameter, it must be submitted for further evaluation considering the severity of the deflection, structural integrity, environmental conditions, and design life of the pipe. If the pipe deflection exceeds 7.5% of the nominal diameter, the pipe must be remediated or replaced.

Additional requirements for thermoplastic pipes are included in Figure 15, which provides information regarding the various applications, maximum fill heights, and initial backfill and bedding quantities.

Figure 15. Requirements for thermoplastic pipes [*28*]



STORM DRAIN INSTALLATIONS			
PIPE TYPE	MAX. FILL HEIGHT (FT)	INITIAL BACKFILL TYPE	FOUNDATION BACKFILL TYPE
HDPE	20	STRUCTURAL	CLASS II B2 OR BETTER
PVC	25	STRUCTURAL	CLASS II B3 OR BETTER
PP	25	STRUCTURAL	CLASS II B3 OR BETTER

SIDE DRAIN (DRIVEWAY) INSTALLATIONS (FILL HEIGHTS UP TO 10-FT)			
PIPE TYPE	MAX. FILL HEIGHT (FT)	INITIAL BACKFILL TYPE	FOUNDATION BACKFILL TYPE
HDPE	10	CLASS II B2 OR BETTER	CLASS II B2 OR BETTER
PVC	10	CLASS II B3 OR BETTER	CLASS II B3 OR BETTER
PP	10	CLASS II B3 OR BETTER	CLASS II B3 OR BETTER

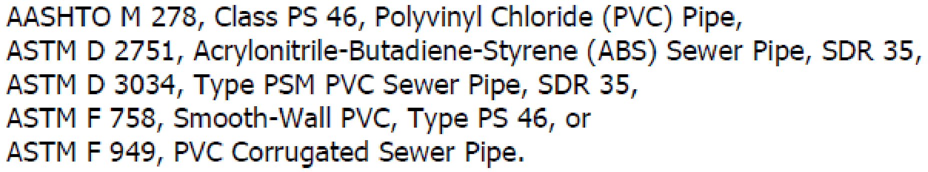
SIDE DRAIN (DRIVEWAY) INSTALLATIONS (FILL HEIGHTS ABOVE 10-FT)			
PIPE TYPE	MAX. FILL HEIGHT (FT)	INITIAL BACKFILL TYPE	FOUNDATION BACKFILL TYPE
HDPE	20	STRUCTURAL	CLASS II B2 OR BETTER
PVC	25	STRUCTURAL	CLASS II B3 OR BETTER
PP	25	STRUCTURAL	CLASS II B3 OR BETTER

INITIAL BACKFILL & BEDDING QUANTITIES		
NOMINAL SIZE (IN.)	INITIAL BACKFILL (FT^3/LF)	BEDDING (FT^3/LF)
12	2.97	0.83
15	3.80	0.96
18	4.73	1.08
24	6.86	1.33
30	9.34	2.38
36	12.18	2.75
42	15.38	3.13
48	18.93	3.50

Minnesota

The Minnesota Department of Transportation gives insight through a Technical Memorandum [*29*] and the Standard Specifications for Construction [*30*] into the use of plastic pipes for storm sewers and culverts. Its purpose is to provide updated design criteria on the use of plastic pipe for storm sewers and culverts. Information is given for the use of corrugated polyethylene (PE) pipe, polypropylene (PP) pipe, and polyvinyl chloride (PVC) pipe. It also gives insight into the minimum and maximum cover requirements. The thermoplastic materials meeting the appropriate standard to be used are listed in Figure 16.

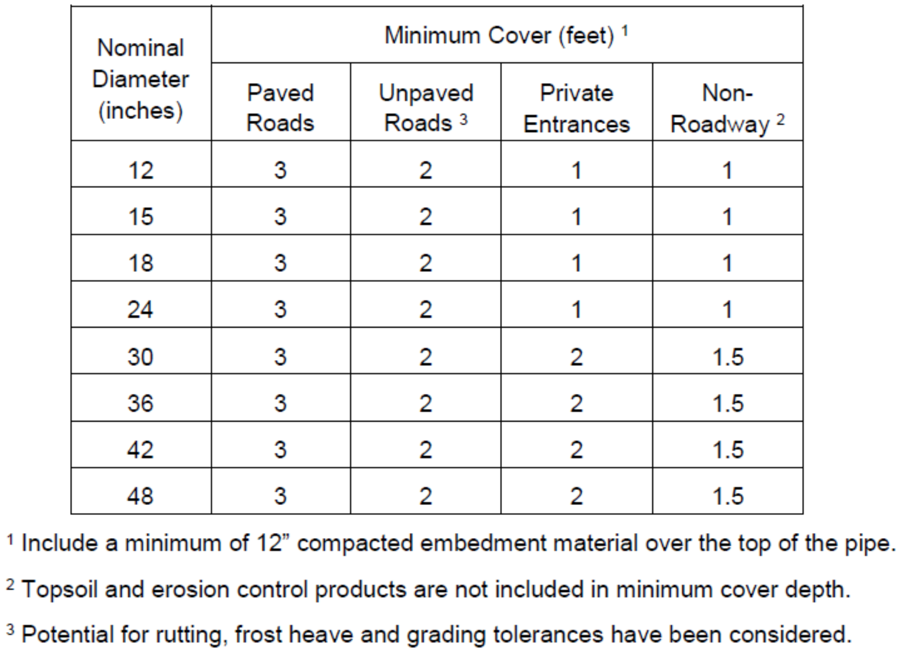
Figure 16. Thermoplastic pipes to be used as pipe sewers or subsurface drains [*30*]



AASHTO M 278, Class PS 46, Polyvinyl Chloride (PVC) Pipe,
ASTM D 2751, Acrylonitrile-Butadiene-Styrene (ABS) Sewer Pipe, SDR 35,
ASTM D 3034, Type PSM PVC Sewer Pipe, SDR 35,
ASTM F 758, Smooth-Wall PVC, Type PS 46, or
ASTM F 949, PVC Corrugated Sewer Pipe.

For use as culverts or pipe sewers, corrugated high-density polyethylene (HDPE) dual-wall pipe meeting the requirements of the AASHTO M 294 Type "S" and Section 12 of the *AASHTO Bridge Design Specifications* pipe must be provided. PVC pipes for use as culverts or pipe sewers must adhere to ASTM F 794, ASTM F 949, and Section 12 of the *AASHTO Bridge Design Specifications*. The minimum cover requirements for plastic pipes for different areas are provided in Figure 17. In cases where buoyancy potential exists, the minimum cover requirements are given in Figure 18 for different plastic types. Finally, Figure 19 summarizes the maximum cover values for different types of plastic materials according to pipe diameters.

Figure 17. Minimum cover requirements for plastic pipes [*29*]



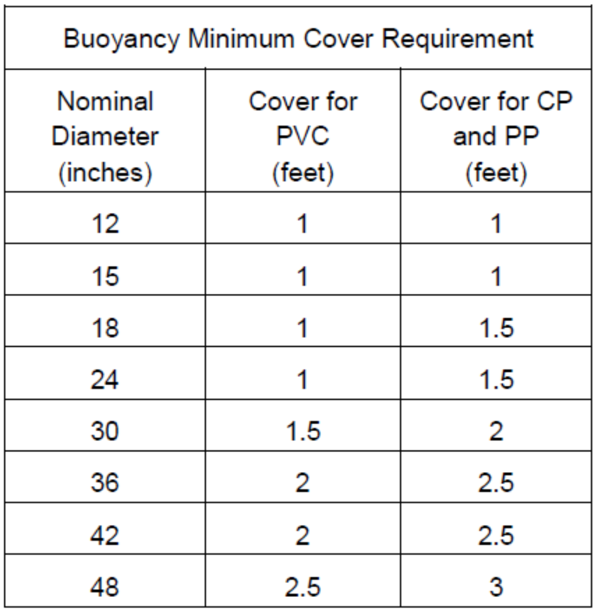
Nominal Diameter (inches)	Minimum Cover (feet) [1]			
	Paved Roads	Unpaved Roads [3]	Private Entrances	Non-Roadway [2]
12	3	2	1	1
15	3	2	1	1
18	3	2	1	1
24	3	2	1	1
30	3	2	2	1.5
36	3	2	2	1.5
42	3	2	2	1.5
48	3	2	2	1.5

[1] Include a minimum of 12" compacted embedment material over the top of the pipe.

[2] Topsoil and erosion control products are not included in minimum cover depth.

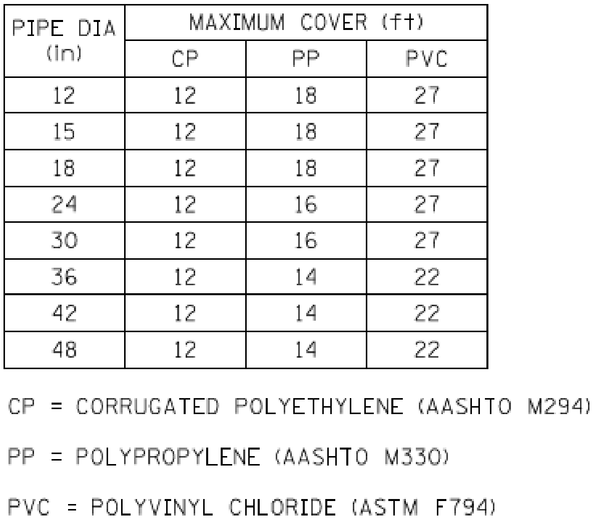
[3] Potential for rutting, frost heave and grading tolerances have been considered.

Figure 18. Minimum cover requirements for plastic pipes with buoyancy potential [*29*]



Buoyancy Minimum Cover Requirement		
Nominal Diameter (inches)	Cover for PVC (feet)	Cover for CP and PP (feet)
12	1	1
15	1	1
18	1	1.5
24	1	1.5
30	1.5	2
36	2	2.5
42	2	2.5
48	2.5	3

Figure 19. Maximum cover requirements for plastic pipes [*29*]



PIPE DIA (in)	MAXIMUM COVER (ft)		
	CP	PP	PVC
12	12	18	27
15	12	18	27
18	12	18	27
24	12	16	27
30	12	16	27
36	12	14	22
42	12	14	22
48	12	14	22

CP = CORRUGATED POLYETHYLENE (AASHTO M294)

PP = POLYPROPYLENE (AASHTO M330)

PVC = POLYVINYL CHLORIDE (ASTM F794)

Table 11 summarizes the allowed pipe materials, allowed applications, maximum pipe diameters, and restrictions in cover and fill height for different DOT in several states.

Table 11. Application and maximum diameters for thermoplastic pipes for different states

State	Material	Cross drain	Side road & entrance	Storm sewer	Underdrain and Basedrain (type)	Underdrain and Basedrain outlet (type)	Unspecified use	Comments
Kansas [31]	PVC-PS100	—	—	—	J[3]	K[3]	—	—
	PVC-PS46	—	—	—	H[3]	—	—	—
	PE-PS50	—	—	—	T[3]	—	—	—
	PE	60" max[1]	60" max	60" max[2]	—	—	—	—
	PVC	48" max[1]	48" max	48" max[2]	H	—	—	—
	PP	60" max[1]	60" max	60" max[2]	—	—	—	—
Illinois [32]	PVC	48" max	—	48" max	—	—	—	up to 30' cover
	CPVC	36" max	—	36" max	—	—	—	up to 35' cover
	PE	48" max	—	48" max	—	—	—	up to 20' cover
	CPE	48" max	—	48" max	—	—	—	up to 10' cover
	CPP	48" max	—	48" max	—	—	—	up to 15' cover
Maine	HDPE	—	—	—	—	—	60" max	—
	PP	—	—	—	—	—	60" max	—
Vermont	CPE	—	—	—	—	—	60" max	—
	CPP	—	—	—	—	—	42" max	—
South Carolina [33, 34]	HDPE	60" max	—	—	—	—	—	Cover: min: 2.7', max: 14'
Minnesota [29]	CPE	48" max[4]	48" max[4]	48" max[5]	—	—	—	up to 12' cover
	PP	48" max[4]	48" max[4]	48" max[5]	—	—	—	up to 14' cover
	PVC			48" max	—	—	—	up to 22' cover
Alabama [35]	HDPE	NA	36" max	36" max	—	—	—	min. cover: 24" max. fill height: 25'
	HPPP	NA	36" max	36" max	—	—	—	
Louisiana [36, 37]	RPVC	48” max 24" min	48” max 18" min	48” max 15" min	—	—	—	min. cover: 12" [7]max. fill height: 5'
	CPEPDW/PP[6]	48” max 24" min	48” max 18" min	—	—	—	—	
Florida [22]	PVC	48" max	48" max	48" max	—	—	—	—
	CHDPE	60" max	60" max	60" max	—	—	—	—
	PP[8]	60" max	60" max	60" max	—	—	—	min. cover: 24"
	HDPE	—	48" max	48" max	—	—	—	

Georgia [28]	PP	—	48" max	48" max	—	—	—	min. cover: 24" max. fill height: 20' for HDPE, 25' for PVC and PP
	PVC	—	48" max	48" max	—	—	—	
	CPVC	—	36" max	36" max	—	—	—	
Texas [38]	PVC[9]	36" max	36" max	—	—	—	—	—
	HDPE[9]	36" max	36" max	—	—	—	—	—
	PP[9]	36" max	36" max	—	—	—	—	—
Arkansas [39, 40]	CHDPE	48" max	48" max	—	—	—	—	[10]min cover: 3', max fill: 15'
	CPVC	36" max	36" max	—	—	—	—	[10]min cover: 3', max fill: 40'
	CPP	60" max	60" max	—	—	—	—	[10]min cover: 3', max fill: 16'
Mississippi [41, 42]	CHDPE	48" max	48" max	48" max	—	—	—	[11]min cover: 21", max fill: 25'
	CPVC	—	—	—	—	—	—	—
Kentucky [43, 44]	CHDPE	48" max	48" max	—	—	—	—	[12]min cover: 2', max fill: 10'
	PVC	48" max	48" max	—	—	—	—	[12]min cover: 2', max fill: 20'
	CPP	—	—	—	—	—	—	-
Tennessee [45–47]	HDPE	60" max	60" max	60" max	—	—	—	[10]min cover: 3'
	PVC	36" max	36" max	36" max	—	—	—	[10]min cover: 3'
	PP	60" max	60" max	—	—	—	—	[10]min cover: 3'
West Virginia [48, 49]	PP	60" max	—	—	—	—	—	—
	HDPE	60" max	—	—	—	—	—	—
	PVC	—	—	—	—	—	—	—
Virginia [50, 51]	PVC	36" max	36" max	36" max	—	—	—	[10]min cover: 18", max fill: 34'
	PE	60" max	60" max	60" max	—	—	—	[10]min cover: 18", max fill: 10'
	PP	60" max[12]	60" max[12]	60" max[12]	—	—	—	[10]min cover: 18", max fill: 12'
North Carolina [52, 53]	HDPE	60" max	60" max	60" max	—	—	—	[13]min cover: 2', max fill: 17'
	PVC	36" max	36" max	36" max	—	—	—	[13]min cover: 2', max fill: 30'

Notes

[1] Except on crossroads on all freeways and expressway routes, and other routes where annual ADT > 3,000 [54]

[2] Except under paved traveled way of freeways and expressway routes, and any other routes where annual ADT > 3,000 [54]

[3] Letter signifies structure type designation as shown in Kansas Standard Specifications for State Road & Bridge Construction - 2015, Division 800 [55]

[4] Allowed where ADT < 5,000 or unpaved roads [29]

[5] No ADT restrictions [29]

[6] Allowed where ADT < 3,000 [36]

[7] Maximum fill height for CPEPDW: 5' and RPVC: 15' for diameters 12" - 48" [*56*]	
[8] See Table 10 for requirements for Class II (100-year design life) PP [*22*]	
[9] To be used with Phase I restrictions [*38*]	
[10] Based on 36" diameter pipe. Minimum cover based on construction loads.	
[11] Based on 48" diameter pipe. Maximum cover for cross drains.	
[12] PP 12" to 30" must be double wall. PP 36" to 60" (inclusive) must be triple wall.	
[13] Based on 36" diameter pipe.	
Definitions	
PVC: Polyvinyl Chloride	RPVC: Ribbed Polyvinyl Chloride
CPVC: Corrugated Polyvinyl Chloride	CPEPDW: Corrugated Polyethylene Pipe Double Wall
PE: Polyethylene	CHDPE: Corrugated High-Density Polyethylene
CPE: Corrugated Polyethylene	PP: Polypropylene
CPP: Corrugated Polypropylene	ADS: Advanced Drainage Systems
HDPE: High-Density Polyethylene	NA: Not allowed
HPPP: High Performance Polypropylene	PS: Pipe stiffness

Task 4. Comparison Between Concrete and Plastic Pipes

When comparing plastic pipes to reinforced concrete pipes, there are many aspects to take into consideration. Table 12 is a comparison between thermoplastic pipes conforming to AASHTO M 294 [*6*], AASHTO M 278 [*57*] and following installation guidelines established in ASTM D 2321 [*20*], and reinforced concrete pipes conforming to ASTM C 76 [*2*] and following installation guidelines established in ASTM C 1479 [*58*]. Aspects such as minimum cover, minimum trench width, backfill material, installation rate, and product weight are used for the comparison.

Table 12 indicates that the soil materials, minimum soil envelope, and minimum spacing between multiple lines of pipes is the same for both plastic and reinforced concrete pipes. The minimum cover requirement depends on the internal diameter of the pipes, but it is required that at least 1 ft. is installed above the pipe. The installation rate of plastic pipes is more than 2 times faster than reinforced concrete pipes. Considering pipe diameters from 4 in. to 15 in., plastic pipes weight ranges from 7 to 60 lb/ft. For the same diameters, reinforced concrete pipes' weight ranges from 15 to 120 lb/ft., which approximately doubles the plastic pipes' weights. Finally, the same design service life can be accomplished for both materials. In summary, the most incidental differences between plastic and concrete pipes are installation times and product weights. These are expected to affect installation costs as smaller equipment can be used for plastic pipes and could potentially be used for less time.

Table 12. Comparison between polypropylene and reinforced concrete pipe

	AASHTO Section	Thermoplastic Pipes	Concrete pipes
Soil material	12.4.1.3 [*18*]	A-1, A-2, A-3 (GW, GP, SW, SP, GM, SM, GC, SC)	
Standard	12.4.2.8 / 12.4.2.3 [*18*]	AASHTO M 294, AASHTO M 278	ASTM C76
Type	12.4.2.8 / 12.4.2.3 [*18*]	PE, PVC	Precast concrete pipes
Minimum trench	12.6.6.1 [*18*]	Maximum of: OD + 16 in. or 1.25*OD + 12 in.	Minimum OD at both sides
Minimum soil envelope (embankments)	12.6.6.2 [*18*]	If diameter D < 2 ft., D/1 ft. If D = 2-12 ft., 2 ft. If D > 12 ft., 5 ft.	
Minimum cover[1]	12.6.6.3-1 [*18*]	Unpaved roads: ID/8 ≥ 12 in. Paved roads: ID/2 ≥ 24 in.	Unpaved roads: OD/8 ≥ 12 in. Bottom of rigid pavement ≥ 9 in.
Compaction		According to Table 13	According to Table 14
Minimum spacing between multiple lines of pipe	12.6.7 [*18*]	If diameter D < 2 ft., 1 ft. If D = 2 - 6 ft., D/2 ft. If D > 6 ft., 3 ft.	
Installation rate [*59*]	—	200 feet/day per RS Means	88 feet/day per RS Means
Product weight	—	7 - 60 lb/ft.	15 - 120 lb/ft.
Service life	—	100 years	100 years

Notes:

ID: inside diameter

OD: Outside diameter

[1] For thermoplastic pipes, taken from the top of rigid pavement or bottom of flexible pavement

Table 13. Soil classes and compaction requirements for thermoplastic pipes [*20*]

Soil group	Soil class	AASHTO	Compaction	Minimum cover
Crushed rock, angular: 100% P 1-1/2", <15% P #4, <25% P 3/8", <12% P #200	Class I	—	Uncompacted but worked into haunch zone to assure complete placement	24 in. or one diameter (whichever is larger)[1]
Clean, coarse grained soils: SW, SP, GW, GP, <12% P #200	Class II	A1, A3	85% SW or SP Compact GW or GP with at least two passes of compaction equipment	36 in. or one diameter (whichever is larger)[1]
Coarse grained soils with fines: GM, GC, SM, SC, <12% P #200 Sandy or gravely fine-grained soils: CL, ML, >30% R #200	Class III	A-2-4, A-2-5, A-2-6, or A-4 or A-6 soils >30% R #200	90%	24 in. or one diameter (whichever is larger)[1]
Fine-grained soils: CL, ML, <30% R #200	Class IV	A-2-7, A-4, or A-6 with <30% R #200	95%	24 in. or one diameter (whichever is larger)[1]
MH, CH, OL, OH, PT	Class V Not for use as embedment	A5, A7	—	—

[1] At least 48 in. must be provided before using a hydrohammer for compaction.

Table 14. Standard trench installation and minimum compaction requirements for concrete pipes [*58*]

Installation Type	**Bedding Thickness**	**Haunch and outer bedding**	**Lower side**
Type I	OD/2 ft. minimum but > 3 in.; if rock encountered, use OD/1 ft. min but > 6 in.	95% SW	90% SW, 95% ML, or 100% CL, or natural soil of equal firmness
Type II	OD/2 ft. minimum but > 3 in.; if rock encountered, use OD/1 ft. min but > 6 in.	90% SW or 95% ML	85% SW, 90% ML, or 95% CL, or natural soil of equal firmness
Type III	OD/4 ft. minimum but > 3 in.; if rock encountered, use OD/1 ft. min but > 6 in.	85% SW, 90% ML, or 95% CL	85% SW, 90% ML, or 95% CL, or natural soil of equal firmness
Type IV	No bedding required except if rock encountered, use OD/2 ft. min but > 6 in.	No compaction required except if CL used, then use 85% CL	85% SW, 90% ML, or 95% CL, or natural soil of equal firmness

Conclusions and Recommendations

A review of DOTD and other state agency specifications were performed to define how plastic pipes have been introduced and how they vary across the U.S. Table 1 summarizes and compares the specifications of concrete and plastic pipe for DOTD, along with how they changed from the last specification version to the most recent 2016 version. These specifications for plastic pipes are in line with other state agencies and AASHTO and ASTM specifications.

To compare concrete and plastic pipes, it is indicated that the minimum soil envelope and the minimum spacing between multiple lines of pipes are the same for both plastic and reinforced concrete pipes. The minimum cover requirement depends on the internal diameter of the pipes, but it is required that at least 1 ft. is installed above the pipe. The installation rate of plastic pipes is more than 2 times faster than reinforced concrete pipes. Considering pipe diameters from 4 to 15 in., plastic pipes weight ranges from 7 to 60 lb/ft. For the same diameters, reinforced concrete pipes' weight ranges from 15 to 120 lb/ft., which approximately doubles the plastic pipes' weights. Finally, the same design service life can be assumed for both materials. The most incidental differences between plastic and concrete pipes are installation times and product weights. These are expected to affect installation costs as smaller equipment can be used for plastic pipes and could potentially be used for less time.

For all the considered plastic material pipes, the deflection value is lower than the allowable when using the initial modulus of pipe material. When using the long-term modulus value, the deflection increases towards the limits of compressive strain for both HDPE and PP pipes. In particular, the results of these example calculations are in accordance with the evaluation of HDPE pipes by Abolmaali et al. [*19*] that shows long-term damage, especially excessive deformation in Houston, Texas. As a result, it is imperative to require post-installation and long-term inspections for plastic pipe, especially for projects that include HDPE and PP. This will provide feedback to the design engineers at DOTD on performance. Based on Abolmaali et al. [*19*], inspections using a high-intensity lighting inspection camera can be used to determine the failure mode and deformations can be quantified using a pipeline laser profiling unit. An additional recommendation stemming from this literature review was the lack of documented field performance for plastic pipes in Louisiana. Beyond specifications and design life, quantifying field performance will be beneficial when deciding which type of pipe to use.

DOTD specifications provide guidance for the appropriate implementation of thermoplastic pipes used for cross drains, side drains, and storm drains that follows the state-of-practice. Several Engineering Directives and Standards (EDSM) and BM-01 Standard Plans summarize the most relevant aspects of the DOTD specifications and provide additional insight for the use in the field. EDSM II.2.1.1 states that a 70-year design life can be used for highways ordinarily requiring 50-year design life if the fill height on the cross drain is greater than 10 ft. Florida DOT has implemented 100-year design life for polypropylene pipe if the extensive requirements in Table 10 are met, which are based on slow crack growth resistance testing and tests to verify that the anti-oxidant package would last longer than the desired design life. In addition, FDOT has also implemented similar testing for a 100-year design life HDPE pipe. Other states, such as Texas, Kansas, and Minnesota, also permit PP to be used in cross-drain applications but they impose ADT limits (Texas < 2000, Kansas < 3000, and Minnesota < 5000). Additionally, Virginia allows PP and specifies that it must be double wall (diameters 12 in. to 30 in.), and triple wall if the pipe has diameters ranging from 36 in. to 60 in.. As a result, the outcome of this survey of other state agencies indicates that PP pipe can be used in Louisiana as outlined in the next version of EDSM guidelines (in preparation), where PP is allowed to replace corrugated polyethylene pipe double wall (CPEPDW). CPEPDW is currently used for cross drain (service life of 50 years) and side drains (service life 30 years except for bridge drains that are 50 years), where the traffic volume is less than 3,000. The service life should remain at the current design life of 30 years or 50 years as promulgated in the EDSM specifications. If a longer service life is considered, the testing protocol should follow Florida DOT because it uses stress crack resistance and antioxidant depletion for evaluating long-term performance. Field performance documentation is also necessary to substantiate post-installation and long-term performance.

The PP pipe modulus reduces drastically from initial to long-term conditions (84% reduction) and the deflection increases ~2.4 times. The PVC pipe modulus reduces only 66% and the deflection increases ~1.4 times. PP and PE materials have similar results as PE pipe modulus reduces 81% but the deflection is increased by ~2.5 times. These design values and calculations can help to grasp how the different pipe materials might perform in practice, but experimental (field and laboratory) data is advised.

To facilitate and fast track implementation of PP pipe with DOTD engineers, a track record of proven performance may be required through a demonstration project(s). An example demonstration project involves a low volume road (ADT < 3000), where the PP pipe is installed, instrumented, and monitored to evaluate its efficacy with other plastic pipes. In particular, a demonstration project specifically focused on the cross drain application could be more valuable for DOTD engineers because a major focus of cross drains is the dip that may form over the roadway. Demonstrating that the dip is limited and performance is satisfactory will assist DOTD in considering and selecting PP pipes as an alternative.

Acronyms, Abbreviations, and Symbols

Term	**Description**
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
CPEPSW	Corrugated Polyethylene Pipe Single Wall
CPEPDW	Corrugated Polyethylene Pipe Double Wall
DOT	Department of Transportation
FHWA	Federal Highway Administration
ft.	foot (feet)
HDPE	High-Density Polyethylene
in.	inch(es)
ksi	kilopound per square inch
DOTD	Louisiana Department of Transportation and Development
lb	pound(s)
LRFD	Load and Resistance Factor Design
LL	Liquid Limit
LTRC	Louisiana Transportation Research Center
NCHRP	National Cooperative Highway Research Program
OC	Organic Content
PE	Polyethylene
PI	Plastic Index
psi	pound(s) per square inch
PVC	Polyvinyl Chloride
PVCP	Polyvinyl Chloride pipe
QA/QC	Quality Assurance/Quality Control
RPVCP	Ripped Polyvinyl Chloride pipe

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