NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 429

HDPE Pipe: Recommended Material Specifications and Design Requirements

Transportation Research Board
National Research Council

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Report 429

HDPE Pipe: Recommended Material Specifications and Design Requirements

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Planning and Administration
Highway and Facility Design
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Soils, Geology and Foundations
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Staff
Transportation Research Board

This report documents the validation of the single-point notched constant tensile load (SP-NCTL) test as a measure of slow crack-growth resistance under sustained loading of high density polyethylene (HDPE) resins—including compositions containing postconsumer resins (PCR)—that are intended for nonpressure drainage pipes and the calibration of minimum slow crack-growth resistance requirements with the results of actual experience. The contents of this report are, therefore, of immediate interest to both highway and rail transit professionals responsible for designing, installing, inspecting, maintaining, and upgrading nonpressure drainage pipes. The report is also of interest to those charged with specifying materials for such pipe, setting budgeting goals, and making policy.

The Geosynthetic Research Institute (GRI) of Drexel University in Philadelphia, Pennsylvania, was awarded NCHRP Project 4-24, "HDPE Pipe Material Specifications and Design Requirements" to undertake this research. GRI was assisted in this effort by Simpson Gumpertz & Heger Inc. of Arlington, Massachusetts. The research team conducted this research and authored the report; NCHRP Project Panel 4-24 wrote the scope of work and reviewed the report, and the necessary majority accepted the report.

The report includes recommended modifications, based on the findings of this research, to the current AASHTO Standard Specification for Corrugated Polyethylene Pipe: M 294; AASHTO Standard Specification for Highway Bridges: Section 18; and AASHTO LRFD Bridge Design Specifications. Among the recommended modifications are revised resin cell classifications and an additional environmental stress crack resistance evaluation using the SP-NCTL test. The report also includes recommended minimum failure times for the SP-NCTL test for resin used in the manufacture of HDPE drainage pipe. A recommended minimum failure time for the SP-NCTL test is included for resin used to manufacture Types C- and S- helical pipes to provide a baseline requirement for accepting possible future overseas HDPE pipe production—this type of pipe is no longer produced in the United States. The appropriate AASHTO bodies will consider the recommendations presented in this report, along with other relevant information, before any specification modifications are adopted.

The report stresses the necessity of controlling procedures for installing HDPE drainage pipe to control localized overstressing. This research did not investigate smaller diameter HDPE pipes; therefore, there are no recommendations in the report for pipes less than 300 mm (AASHTO M 252 Drainage Tubing). Furthermore, at the present time, it is judged to be premature to recommend the SP-NCTL test be the Stress Crack Resistance test for finished HDPE corrugated drainage pipes. Since this is the first major investigative effort designed to relate the results of a crack resistance index test against the quality of field performance, finer tuning of the minimum slow crack-growth requirements for HDPE resins intended for use in HDPE corrugated drainage pipe may occur as the technology matures and as additional observations of field experience are noted.

CONTENTS

AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 04-24 by the Geosynthetic Research Institute, Civil and Architectural Engineering, Drexel University, and Simpson Gumpertz & Heger Inc. (SGH Inc.). Drexel University was the contractor for this study. The work undertaken at SGH Inc. was under a subcontract with Drexel University.

Y. Grace Hsuan, Associate Professor of Civil and Architectural Engineering, Drexel University, was the principal investigator. Timothy J. McGrath, Principal of SGH Inc. was the subcontractor.

The work was done under the general supervision of Professor Hsuan. The work at SGH Inc. was done under the general supervision of Dr. McGrath with the assistance of Dan Valentine. The work at Drexel University was under the supervision of Professor Hsuan, with the assistance of Robert Valorio and Danny Liou.

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation

HDPE PIPE: RECOMMENDED MATERIAL SPECIFICATIONS AND DESIGN REQUIREMENTS

SUMMARY

The objective of this study was to evaluate the stress crack resistance (SCR) of high density polyethylene (HDPE) corrugated pipes and correlate it with observed field performance. Because of the limitation of the current environmental stress crack resistance (ESCR) tests (ASTM D 1693), an alternative test, the single-point notched constant tensile load (SP-NCTL) test (ASTM D 5397-Appendix), was used in the study. The research further explored the specific conditions of the SP-NCTL test to evaluate HDPE corrugated pipes and to establish the minimum SCR requirements by calibrating the test with the field performance of the pipe.

The following steps were taken to accomplish the research objectives:

1. Discussing the modification of cell classification in different AASHTO specifications and the recent adoption of a new SCR test (ASTM F 1473) in ASTM D 3350.
2. Compiling information on the overall performance of HDPE corrugated pipes through a questionnaire.
3. Identifying sites with cracked pipes through a second questionnaire developed specifically for that purpose.
4. Performing field investigations at identified sites and collecting data on the pipe conditions and retrieving cracked pipe samples.
5. Conducting laboratory testing to evaluate material properties and the SCR of both commercially available new pipe samples and retrieved field samples.
6. Investigating the effects of orientation, bending, and residual stress on the SCR of finished pipes.
7. Identifying the appropriate test condition for the SP-NCTL test to be used in HDPE corrugated materials.
8. Establishing the minimum criteria for the SP-NCTL test to quality HDPE corrugated pipe resins.

FIELD INVESTIGATIONS

The majority of the responses from the questionnaire expressed a good or satisfactory experience with the overall performance of the HDPE corrugated pipe. The information

provided by the second questionnaire indicated 62 sites with problems associated with deflection, buckling, cracking, and joints. Twenty-nine of these sites were visited, and pipes at twenty sites showed cracking. Cracking occurred in pipe with profile Types C-helical and C-annular, S-helical and S-annular, and S-honeycomb, and with diameters ranging from 300 mm to 1,050 mm. Circumferential cracking was the dominant type, indicating longitudinal stresses. The circumferential cracks in Type S pipes mostly occurred at the junction of the liner and corrugation. The crack grew from the outer surface (interior of the void in the corrugation) through the thickness of the liner. In contrast, longitudinal cracks propagated through both the liner and the corrugation, potentially allowing infiltration of soil into the pipe. Much of the cracking was associated with installation problems that led to excessive deflection and buckling or longitudinal bending. However, there were sufficient cases of cracking under moderate deflection levels to warrant attention to the material quality and product design, as well as to the installation procedure and detailing of pipe junctions with rigid structures. Nineteen pipe samples retrieved from the field were evaluated in various laboratory tests.

LABORATORY TESTING

Fourteen commercially available new pipes and nineteen retrieved field samples were evaluated for their material properties and SCR. The material properties were assessed according to the latest AASHTO M 294 Specification. The majority of the tested samples conformed to the specified values for density, melt index (MI), flexural modulus, and tensile yield strength. However, one-half of the new pipes and one-half of the retrieved pipes failed to pass the current ESCR test, that is, the ASTM D 1693 test. The results indicate materials that comply with the basic property requirements, such as density and melt index, do not necessarily meet the SCR criteria. Thus, the SCR of corrugated pipe materials must be evaluated independently.

The SP-NCTL test was performed on the thirty-three pipe samples. The specific applied stress for the proposed AASHTO recommendations was investigated and a 15% yield stress was determined to distinguish various resin qualities and to produce a reasonable testing time. The results of the SP-NCTL test, that is, the failure time at 15% yield stress, ranged from 0.5 to 1,800 hours, indicating a large variation in SCR behavior of the tested materials. Materials with longer failure times have a greater SCR than those with shorter failure times. Data from retrieved field pipe samples indicated that pipes made from high SCR resins have not exhibited cracking even under a large deflection. This indicates that the SCR of the pipe resin is an important parameter in preventing cracking in the field.

A proposal for minimum failure time of the SP-NCTL test for HDPE resins used in corrugated pipes was established on the basis of data obtained from retrieved pipe samples as well as on the pipe condition and pipe profile. The specific value is defined according to the type of pipe profile:

- For Type C- and S-helical pipes, the minimum average failure time is 400 hr;
- For Type C- and S-annular pipes and Type S-honeycomb pipes, the minimum average failure time is 24 hr; and
- For all types of pipe profiles, statistical variability is accounted for by setting lower minimum test times for individual tests.

For the finished pipe products, the effect of manufacturing process on the SCR was evaluated for Type S-annular pipes. However, helical and honeycomb pipes were not tested. The greatest processing effect was caused by the residual stress in the longitudinal direction of the liner with crack growth from the outer surface through the liner thickness in the circumferential direction. This suggests that residual stress could be one of the factors leading to the circumferential cracking observed in the field. Because of the effect of residual stress, the pipe liner had a shorter failure time than the molded plaque prepared from the same resin material. A maximum reduction factor of 2.3 was found when the test specimens were taken from the pipe liner in the longitudinal direction and notched from the outer liner surface.

The findings of this project document the effectiveness of the SP-NCTL test in determining the SCR of HDPE corrugated pipe resins. Minimum criteria are proposed based on the field performance of these pipes. Recommendations for incorporation into the current AASHTO Standard Specification for Corrugated Polyethylene Pipe: M 294; AASHTO Standard Specification for Highway Bridges (Section 18); and AASHTO LRFD Bridge Design Specifications are included as Appendix I.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

RESEARCH PROBLEM STATEMENT

High density polyethylene (HDPE) is being used as drainage pipe material because it is lightweight, corrosion resistant, easy to install, and has a low maintenance cost. The design of HDPE corrugated drainage pipe is based on the assumption that the pipe will deform and thus relieve stress. Consequently, ductility is an essential parameter to accommodate allowable deflection during the pipe's service life. HDPE resins with low ductility can lead to unexpected cracking in the pipe, brought on by a process called "slow crack growth." To minimize such cracking, the stress crack resistance (SCR) of HDPE resins must be properly evaluated.

Currently, the AASHTO Standard for Bridge and Material Specifications includes the environmental stress crack resistance (ESCR) test, ASTM D 1693, as the control to assess SCR of HDPE resins. However, the ESCR test has many disadvantages that limit the capability of the test. Another test, Hydrostatic Design Basis (HDB), was recently removed from the AASHTO bridge design specifications (Section 18, Soil-Thermoplastic Pipe Interaction Systems) because of its restrictiveness and impracticability for drainage pipes. Therefore, a more practical and reliable test protocol is needed to qualify resins with acceptable SCR under sustained tensile loading. The notched constant tensile load (NCTL) test, ASTM D 5397, which was originally developed for HDPE geomembranes, has been found to be applicable in distinguishing SCR of HDPE drainage pipe materials. The abbreviated version of the test, that is, the single-point (SP-NCTL) test, which was developed for quality control and quality assurance, can be modified for HDPE drainage pipe materials.

OBJECTIVES

The objectives of this project were to explore and, if appropriate, validate the SP-NCTL test as a qualitative predictor of SCR for HDPE resins used in corrugated pipes and to determine the minimum SCR requirements by correlating the test data with field performance of the pipe. To accomplish these objectives, the following tasks were performed:

1. Searched published and unpublished information to establish the current practice for defining acceptable HDPE resins used in the corrugated pipes.
2. Compiled information from state DOTs and other user agencies on overall performance of HDPE corrugated drainage pipes and identified sites with pipes exhibiting stress cracking.
3. Performed detailed field investigations on selected sites by collecting data on pipe conditions and by retrieving cracked samples.
4. Using the NCTL test, determined the failure time at two stress levels in the brittle region for the following two groups of materials:
    a. Samples from a representative range of resins currently permitted by AASHTO and
    b. Retrieved pipe samples.
5. Studied the effect of pipe manufacturing processes on SCR of HDPE resins.
6. Analyzed test data and proposed the minimum failure time for the SP-NCTL test to ensure SCR of HDPE resins used in corrugated drainage pipes.
7. Developed drafts of modified AASHTO specifications to include the SP-NCTL test requirements.

RESEARCH APPROACH

The research approach for this project included developing questionnaires to gather information on the overall performance of HDPE corrugated drainage pipes and to identify sites where cracking had been observed. These questionnaires served two purposes: (1) to document the experiences of users and (2) to identify sites where cracked pipes were located. From the responses, sites for field investigation were identified and visited. Information regarding the field environment and pipe conditions was recorded. Some of the retrieved field samples were selected for further material evaluation in the laboratory.

The evaluation of basic material properties and SCR was performed on both the retrieved field pipe samples and commercially available new pipe materials. The criteria for assessing material properties were in accordance with the latest AASHTO M 294 Specification. Regarding the SCR property, a systematic study was carried out on the NCTL test so that the appropriate applied stress for the SP-NCTL test could be specified.

The minimum failure time for HDPE corrugated pipe resins was established by analyzing the SP-NCTL test data obtained from retrieved field samples. Finally, the related sections in various AASHTO specifications were modified accordingly.

CHAPTER 2

FINDINGS

DEVELOPMENT OF THE SPECIFICATION FOR HDPE CORRUGATED PIPES

Four AASHTO specifications currently specify high density polyethylene (HDPE) resins for corrugated drainage pipes used in transportation applications:

- AASHTO M 252 Standard Specification for Corrugated Polyethylene Drainage Tubing,
- AASHTO M 294 Standard Specification for Corrugated Polyethylene Pipe,
- AASHTO Standard Specification for Highway Bridges (Section 18), and
- AASHTO LRFD Bridge Design Specifications.

Specifications M 294 and Section 18 are for pipe diameters larger than 300 mm, which are commonly used in cross drain and culvert applications. Pipes used in those applications are the primary focus of this research project.

Prior to 1996, the material requirements in the M 294 and Section 18 Specifications were not identical, as pointed out in the NCHRP Project 20-7 Task 68, by Gabriel et al. (*1*). A set of specified cell class was defined in the specifications based on ASTM D 3350. Table 1 shows the old cell class of these two specifications. Also shown in Table 1 is the newly revised cell class, which is encompassed by both M 294 and Section 18. The most noticeable difference between the two old cell classes is the stress crack resistance (SCR) requirement. In Standard M 294, ESCR test was the only requirement with a criterion that allows 50% of the specimens to fail at 24 hr under Condition B. In contrast, Section 18 required the ESCR and HDB tests to assess the SCR of the pipe resin and pipe product, respectively. For the ESCR test, the criterion allows 50% of the specimens to fail at 48 hr under Condition A.

The two different ESCR test requirements created some confusion and controversy. Condition A of the ESCR test is performed on a thicker specimen than for Condition B. For the same resin, testing under Condition A is less severe than Condition B (*2*). However, Section 18 requires pipes to have a HDB value of 6.89 MPa to ensure that no brittle cracks occur within 50 years of service. This raises the SCR requirement for Section 18. In the new unified specification, the HDB test was removed and a higher ESCR cell class was adopted. Furthermore, density and melt index (MI) are made stricter in the revised cell class. The upper density range is limited to 0.955 g/cc. This eliminates homo-polymers and very high density co-polymers, which are extremely sensitive to stress cracking, from being used in this type of product. For the MI, a lower range is selected, which will ensure the use of a relatively higher molecular weight resin, subsequently improving SCR. Although both density and MI requirements are modified, they will not guarantee the SCR of the resin (*3*).

In summary, the revised cell classification shows an improvement in the density and MI properties by defining a stricter specific range. However, the SCR requirement of Section 18 was actually lowered by removing the HDB test. Under these circumstances, a study focusing on the SCR of HDPE corrugated pipes seems to be appropriate.

OVERVIEW OF STRESS CRACK RESISTANCE TESTING

As stated in the previous section, the material requirement in all four AASHTO specifications is based on ASTM D 3350. Any change in this standard could have an impact on these four specifications. In 1997, ASTM D 3350 adopted a new test, ASTM F 1473 (PEN test) to evaluate the SCR of polyethylene gas pipes. Subsequently, the cell class table of the standard was modified, as shown in Table 2. Irrespective of the SCR property, there are two methods included in the standard. These are the ESCR test (ASTM D 1693) and the PEN test (ASTM F 1473). The ESCR test is used to evaluate corrugated HDPE pipe resins. The PEN test is mainly used by the pressure pipe industry.

However, there are some disadvantages to the ESCR test. The three major problems associated with the test are as follows:

- The failure time of an individual test specimen cannot be recorded.
- There is a large standard deviation value.
- The actual stress condition varies throughout the test and is not known, because of stress relaxation in the material.

On the other hand, the PEN test is designed to evaluate the SCR of HDPE resins used in pressure pipes for quality control (QC). An aggressive test condition is configured so that a relatively short failure time can be achieved. The test is performed at a temperature of 80°C, which is the maxi-

TABLE 1 Changes in cell classification in AASHTO M 294 and Section 18 Specifications

Property	Density	MI	Flexural Modulus	Yield Strength	ESCR	HDB
ASTM Method	(D1505) (g/cc)	(D1238) (g/10min)	(D790) (MPa)	(D638) (MPa)	(D3895)	(D2837) (MPa)
AASHTO M 294 (prior to 1996)						
	3	**2**	**4**	**4**	**2**	**0**
	0.941 - 0.955	1.0 - 0.4	552 - 758	21 - 24	condition B 50% at 24 hr	

Note: Compounds that have higher cell classifications in one or more properties are acceptable provided product requirements are met.

	Density	MI	Flexural Modulus	Yield Strength	ESCR	HDB
AASHTO Section 18 (prior to 1996)						
	3	**1**	**5**	**4**	**1**	**2**
	0.941 - 0.955	> 1.0	758 - 1103	21 - 24	condition A 50% at 48 hr	6.89
Revised Cell Class for both M 294 and Section 18						
	3	**3**	**5**	**4**	**2**	**0**
	0.945 - 0.955	< 0.4 - 0.15	758 - 1103	21 - 24	condition B 50% at 24 hr	

TABLE 2 Newly adopted cell class table for ASTM D 3350

Property	Test Method	0	1	2	3	4	5	6	7	8	9
1. Density (g/cc)	D 1505	Unspecified	0.910 - 0.925	0.926 - 0.940	0.941 - 0.955	> 0.955					Specify value
2. Melt Index (g/10 min)	D 1238	Unspecified	>1.0	1.0 - 0.4	< 0.4 - 0.15	< 0.15					Specify value
3. Flexural Modulus(MPa)	D 790	Unspecified	<138	138 - 276	276 - 552	552 - 758	758 - 1103	> 1103			Specify value
4. Yield Strength (MPa)	D 638	Unspecified	<15	15 - 18	18 - 21	21 - 24	24 - 28	> 28			Specify value
5. Resistance to Slow Crack Growth											
Method A (hr): Compression mold 2.4 MPa, 80°C notch depth (Table 1 in F1473)	F 1473	Unspecified				0.15	1	3	10	30	Specify value
Method B:	D 1693	Unspecified									Specify value
a. Test condition			A	B	C	C					
b. Test duration (hr)			48	24	192	600					
c. Failure, max, %			50	50	20	20					
6. Hydrostatic Design Basis (MPa) 23°C	D 2837	Unspecified	5.52	6.89	8.62	11.03					Specify value

mum allowable test temperature limit for SCR tests without changing the property of the material. Further, the slow cooling rate used in the compression plaquing procedure (i.e., overnight cooling) yields a very high crystalline material; thus, the SCR of the material decreases. It is believed that this test is probably too severe for HDPE corrugated pipe resins because it may result in an extremely short failure time.

Besides these two SCR tests, an alternative test to evaluate the SCR of polyethylene is the notched constant tensile load (NCTL) test (ASTM D 5397). For QC and quality assurance (QA) purposes, an abbreviated version of the test, a single-point (SP) NCTL test (ASTM D 5397-Appendix) was also developed. The NCTL test was originally designed for evaluating SCR of HDPE geomembranes. The test environment is less aggressive than the PENN test because it uses a lower testing temperature of 50°C. To achieve a reasonably short failure time, a surfactant (10% Igepal solution) is used to accelerate the crack growth. The development of the NCTL test was based on a research study funded by the U.S. Environmental Protection Agency. In the study, the relationship between failure times obtained from the NCTL test and HDPE geomembrane performance in the field was established (*3*). A specification for HDPE geomembranes was developed from the findings of the study (*4*).

Recently, both the NCTL test and the SP-NCTL test were used in a research study to evaluate polyethylene materials intended for pipe applications (*5*). Materials included in the study involved pressure rated HDPE virgin resins, nonpressure rated HDPE resins, and postconsumer resins (PCR). The study demonstrated that the SP-NCTL test could effectively distinguish the SCR of tested materials, particularly by the addition of PCR.

The focus of this project was to further explore the applicability of the SP-NCTL test regarding the SCR of HDPE corrugated pipes.

FIELD PERFORMANCE OF HDPE CORRUGATED PIPES

Questionnaires were developed to (1) assess the performance of HDPE corrugated pipes and (2) identify appropriate sites for sampling and subsequent evaluation of field installed pipe. Approximately 400 questionnaires were sent to the 50 state DOTs, to federal and local agencies, and to engineering consultants. Manufacturers of corrugated HDPE pipes and manufacturers of competing products made up a large portion of the mailing list. This approach allowed the research team to seek out owners and field sites representative of both sides of the controversial issue regarding the SCR property of the resin. At least one contact was identified in each state DOT. The contacts within municipal, county, and private organizations were largely supplied by manufacturers of competing products.

Questionnaire No. 1 was developed to assess the general experience of owners and engineers with corrugated HDPE pipes. Information requested included the type, diameter, and length of pipe installed in an owner's systems, or under a consultant's specifications, and a general assessment (good, satisfactory, or unsatisfactory) of experience with the product.

Questionnaire No. 2 was developed to identify sites with cracked pipe that might be appropriate for inclusion in the testing program. Details sought on Questionnaire No. 2 included information on the condition of the pipe that may have contributed to cracking, such as age, fill height, deflection, buckling, longitudinal bending, and joint problems. All respondents to Questionnaire No. 2 also completed Questionnaire No. 1. The two questionnaires are included as Appendix A of this report, which is not published herein.

A total of 114 responses to Questionnaire No. 1 were received. The questionnaire responses are summarized in Appendix B, Table B-1, which is not published herein. The majority of the responses were provided by personnel working for state DOTs, cities, or counties. Six states expressed limited or no usage of HDPE corrugated pipes. The overall performance experience of five groups: federal agencies, state DOTs, cities, counties, and consultants, are presented in Table 3. Of these groups, only the state DOTs represent a fairly complete population of possible respondents, that is to say, most states are represented. Because the other four groups represent only a small portion of a possible population and were selected to help locate sites with cracked pipe, the responses should not be considered as representative of the entire group.

TABLE 3 Percentage of responses and general experience from each sector of the sources (information was based on data obtained from Questionnaire No. 1)

Source	No. Of Responses (%)[1]	Experience (%)[2]			
		Good	Satisfied	Unsatisfied	np[3]
DOT	61 (54%)	44	47	2	7
Federal	3 (3%)	67	0	0	33
City	12 (10%)	25	17	50	8
County	17 (15%)	24	53	24	0
Consultant	21 (18%)	33	52	5	10

[1] The percentages indicated are based upon a total of 114 responses.
[2] Percentages indicate each individual experience with HDPE corrugated pipes.
For instance, 44% of the 61 DOT responses expressed having a "good" experience.
[3] np = not provided

Even with this bias in the population, only the "city" group has a rating of unsatisfactory of more than 25%.

Sixty-two sites were identified from responses to Questionnaire No. 2. Detailed summaries of the responses are presented in Appendix B, Tables B-2(I) and B-2(II). The apparently high number of responses to Questionnaire No. 2 relative to the number of responses to Questionnaire No. 1 should not be considered as indicative of a failure rate. Responses to Questionnaire No. 1 represent an owner's or designer's entire experience with corrugated HDPE pipe, which is often many miles of pipe and numerous individual installation sites. On the other hand, the number in Questionnaire No. 2 represents sites that exhibit problems. In many cases, the respondent of Questionnaire No. 1 provided more than one response to Question-naire No. 2. Also, many responses to Questionnaire No. 2 were from owners who expressed overall satisfaction with the performance of the product.

The problems identified include cracking, deflection, and buckling, as summarized in Table 4. Most of the sites where cracking was reported also involved high deflection levels in the pipe. Thus, the control of field construction procedures may have been a contributing cause to the observed problems.

Field Investigations

Based on information obtained from Questionnaire Nos. 1 and 2, 29 sites were identified and visited. The primary purpose of the field investigation was to collect samples from sites with cracked pipe for incorporation into the testing program. In some instances, sites were selected for the presence of high deflection and long service time without cracking. In addition, sites with diameters greater than 600 mm were given preference to allow field personnel to enter and determine the condition of cracks. Information regarding the pipe performance, such as age, style of the pipe, deflection, buckling, longitudinal bending, and type of cracking were recorded during the field investigations.

Thirty-four pipe samples were retrieved from the twenty-nine field sites. Table 5 lists the response number and basic information on the 34 pipe samples assembled from field site reports. Additional details are provided in Tables B-1, B-2(I), and B-2(II) of Appendix B. Of the 34 field samples, 24 (70.5%) were helical pipes, 7 (20.5%) were annular pipes and 3 (9%) were honeycomb pipes. The oldest field pipe was a Type-C helical pipe installed 16 years ago. Six pipes had been in service for approximately 1 year. The ages of different types of pipes are shown graphically in Figure 1.

Information regarding the pipe condition, including percent deflection, buckling, bending, and types of cracking is presented in Table 6. Circumferential cracks were the dominant type of cracking, indicating the presence of longitudinal tensile stresses. Cracking often occurred concurrently with deflection. The vertical deflection in cracked pipes varied from 2% to 25%. For Type C-helical pipes, the full circumferential cracking resulted in a separation of the pipe and an actual or potential loss of soil around the pipe. For Type-S pipes, the circumferential cracking typically occurred at the junction between the liner and the corrugation, as illustrated in Figure 2. This type of cracking may not lead to the collapse of the pipe but could affect the hydraulic performance. Type S-honeycomb pipes, which are classified as Type-D pipes

TABLE 4 Pipe problems that were identified (information was based on data obtained from Questionnaire No. 2)

Problems Experienced	No. of Sites
Cracks, deflections, and buckling	13
Cracks and deflections, without buckling	21
Cracks and buckling, without deflections	4
Deflections and buckling, without cracks	6
Cracks only	6
Deflections only	12

TABLE 5 Information obtained from the investigated field sites

Site No.	Response No.	Age (years)	Region	Diameter (mm)	Pipe Style
A	72-11	16	5	600	Type C - helical
B	72-3	13	5	600	Type C - helical
C	101-1	1	5	900	Type S - helical
D	72-1	2	5	600	Type C - annular
E	72-2	3	5	1050	Type S - honeycomb
F	72-12	<1	5	1050	Type S - helical
G	101-2	1	5	1200	Type S - annular
H	101-3	4	5	750	Type S - helical
I	101-4	1	5	600	Type S - annular
J-1	93	7	1	600	Type S - helical
J-2	93	7	1	300	Type S - annular
J-3	93	7	1	900	Type S - helical
K	27	6	1	900	Type S - helical
L	102-1	8	Canada	900	Type C - helical
M	102-2	12	Canada	150	Type C - helical
N	102-3	12	Canada	450	Type C - helical
O	15	10	3	600	Type C - helical
				600	Type S - helical
P	30	1	4	750	Type S - annular
Q	43-4	3	4	900	Type S - helical
R	43-5	3	4	900	Type S - helical
S	85-1	3	4	750	Type S - helical
T	28-2	2	6	600	Type S - helical
U	43-6	2	4	1050	Type S - honeycomb
V	103-1	3	10	750	Type S - helical
W	103-2	2	10	1200	Type S - honeycomb
X1	45	N/A	10	600	Type S - helical
X2	45	N/A	10	600	Type S - helical
X3	45	N/A	10	450 & 600	Type S - helical
Y	45	N/A	10	600	Type S - annular
Z	45	N/A	10	450 & 600	Type S - annular
AA	45	N/A	10	600	Type C - helical
BB	45	10	10	600	Type C - helical
CC	45	12	10	600	Type C - helical

Note: Type C - This type of pipe has a full circular cross-section, with a corrugated surface both inside and outside.
Type S - This type of pipe has a full circular cross-section, with an outer corrugated pipe wall and a smooth inner liner.
Type S- Honeycomb is also referred to as Type D pipe in some of the AASHTO specifications.

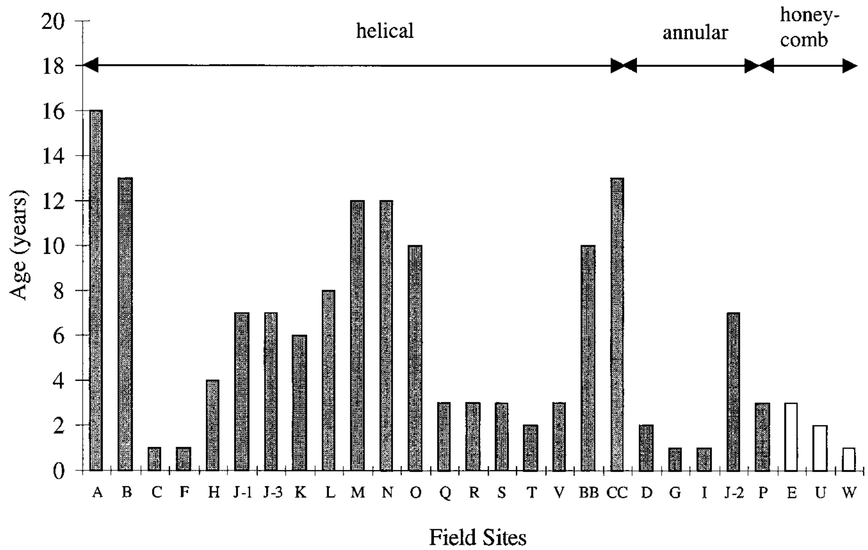

Figure 1. The ages of retrieved pipe samples according to corrugation profile.

in some AASHTO specifications, showed both longitudinal and circumferential cracks in the inner liner, indicating that the pipe was subjected to a complex stress field. (Note that pipes with the honeycomb profile are referred to as “Type S-honeycomb pipes” throughout this report.)

Longitudinal cracking was also observed in Type C-helical and C-annular pipes and in Type S-annular and S-honeycomb pipes, indicating the existence of a circumferential stress at certain sections of the pipes. This type of cracking allows soil to enter the pipe and represents a potential loss of structural capacity. The longitudinal cracks are generally associated with high deflection. In addition, buckling is usually associated with high deflection and was observed at ten sites. Significant longitudinal bending was observed at four sites.

The cracked regions of the pipe were removed from the inside of the pipe using a small saw, as shown in Figure 3. When field conditions permitted, additional pipe material for laboratory evaluation was taken from the end of the pipe that extended from the fill section.

The field investigation also provided an opportunity to make a direct correlation between installation conditions and observed behavior. Problems included the following:

- Deflection—Deflection results from the lack of control of construction procedures and the use of poor backfill materials.
- Erosion at outlet ends of culverts unprotected by headwalls—This erosion often resulted in significant loss of material and longitudinal bending and cracking of the corrugated HDPE pipe.
- Erosion as a result of joint leakage—In some of the above cases, it is believed, but not verified, that leakage through joints contributed to erosion around a pipe outlet. Most of the joints inspected were the older wraparound coupling type. The joint technology for corrugated HDPE has developed a great deal in the recent past, and the field observations may not be indicative of current practice.

The above problems with erosion at outlets and with joints are also known to be issues with other types of pipe.

EVALUATION OF COMMERCIALLY AVAILABLE NEW PIPES

Fourteen pipe samples and the corresponding resin pellets were obtained from four corrugated pipe manufacturers. Table 7 shows the pertinent information on the 14 samples. Materials used in manufacturing the 14 pipes involve 9 virgin resins (VR-1 to VR-9), 1 reprocessed resin (RP-1) and 2 postconsumer resins (PCR-1 and PCR-2). The corrugation geometry of each type of pipe is presented in Appendix C.

The primary focus of the evaluation is to assess the SCR of pipe materials using the NCTL test, ASTM D 5397. Additionally, properties of the pipe materials were evaluated according to requirements defined in the AASHTO M 294 Specification. The latest required cell class is 335420C, except that the carbon black content shall not exceed 5%, and the density shall not be less than 0.945 g/cm^3 nor greater than 0.955 g/cm^3. With the exception of density, other properties can have a higher cell class. In this study, the oxidation induction time (OIT) test, ASTM D 3895, was added to the list of material tests. Table 8 presents the tests that have been performed on either compression molded plaques or the pipe material itself. Compression molded plaques were made from either resin pellets or pipe pieces according to ASTM D 1928 Procedure C, which is specified by ASTM D 3350. Three 1.8-mm-thick plaques and one 3.2-mm-thick plaque were

TABLE 6 Pipe conditions at the investigated field sites

Site	Type	Approximate Fill Height (m)	Deflection: Horizontal min.	Deflection: Horizontal max.	Deflection: Vertical min.	Deflection: Vertical max.	Buckling	Longitudinal Bending	Cracking
A	C-Helical	0.3	7.29%	8.33%	-6.25%	-12.50%	No	No	Circumferential/Longitudinal
B	C-Helical	1.2 - 1.8	N/A	N/A	N/A	N/A	No	Yes	Circumferential
C	S-Helical	1.2	N/A	4.86%	N/A	-3.13%	No	No	Circumferential
D[1]	C-Annular	Not Applicable					No	No	Longitudinal
E	S-Honeycomb	12 - 13.5	-1.3%	5.1%	-3.3%	-10.0%	Yes	No	Circumferential/Longitudinal
F	S-Helical	1.8 - 2.4	1.8%	10.0%	-5.1%	-19.4%	Yes	No	Circumferential/Longitudinal
G	S-Annular	0.9	3.3%	5.3%	-3.5%	-5.7%	No	No	Circumferential
H	S-Helical	2.3	1.3%	6.7%	-2.1%	-2.1%	No	Yes	Circumferential
I	S-Annular	1.2	N/A	4.2%	N/A	-4.2%	No	Yes	Circumferential
J1[2]	S-Helical	0.6	N/A	N/A	N/A	-25.0%	No	No	Circumferential
J2[2]	S-Annular	0.3	N/A	N/A	N/A	-3.3%	No	No	Circumferential/Longitudinal
J3[2]	S-Helical	1.2	N/A	N/A	N/A	-11.1%	Yes	No	Circumferential
K	S-Helical	1.8 - 2.4	8.3%	13.9%	-11.1%	-16.7%	Yes	No	Circumferential
L	C-Helical	7.5 - 9	N/A	N/A	N/A	-16.7%	Unknown	Unknown	No Crack**
M	C-Helical	0.09	No Deflections Observed				Unknown	Unknown	Unknown
N	C-Helical	0.15	N/A	N/A	N/A	-10.0%	Unknown	Unknown	No Crack**
O	C-Helical	30	N/A	0.4%	N/A	-4.2%	Yes	No	Circumferential
	S-Helical	30	N/A	1.3%	N/A	-4.5%	Yes	No	Circumferential
P	S-Annular	0.9 - 1.2	1.7%	5.0%	-1.5%	-5.0%	No	No	Circumferential
Q	S-Helical	0.3 - 0.6	6.9%	11.1%	-8.3%	-15.3%	Yes	No	Circumferential
R	S-Helical	0.45	-1.4%	13.9%	-2.8%	-16.7%	No	Yes	Circumferential
S	S-Helical	0.9 - 1.2	1.7%	11.7%	-1.7%	-10.0%	No	No	Circumferential
T	S-Helical	0.9	2.1%	13.5%	-2.1%	-13.5%	Yes	No	Tearing
U	S-Honeycomb	0.6 - 1.2	2.4%	9.5%	-7.1%	-20.2%	Yes	No	Circumferential/Longitudinal
V	S-Helical	0.9	No Deflections Observed				No	No	Circumferential
W	S-Honeycomb	0.6 - 1.2	1.0%	3.1%	-6.3%	-10.4%	Yes	No	Circumferential/Longitudinal
X1	S-Helical	1.5 - 1.8	N/A	N/A	N/A	N/A	Unknown	Unknown	Unknown
X2	S-Helical	1.8 - 3	N/A	N/A	N/A	N/A	Unknown	Unknown	Unknown
X3	S-Helical	1.2	N/A	N/A	N/A	N/A	Unknown	Unknown	Unknown
Y	S-Annular	2.4	N/A	N/A	N/A	N/A	Unknown	Unknown	Unknown
Z	S-Annular	3	N/A	N/A	N/A	N/A	Unknown	Unknown	Unknown
AA[3]	C-Helical	pipe cracked prior to installation					N/A	N/A	Circumferential
BB	C-Helical	1.2	N/A	N/A	N/A	N/A	Unknown	Unknown	Unknown
CC	C-Helical	0.6 - 1.2	N/A	N/A	N/A	N/A	Unknown	Unknown	Unknown

** Information was provided by the local pipe manufacturer.
A negative deflection value represents a shortening.
A positive deflection value represents an elongation.

[1] Pipe used as formwork for concrete columns.
[2] Deflection and buckling information were provided by others.
[3] Unused pipe found in materials storage yard.
Unknown = Result of inability to enter pipe; N/A = Not Available

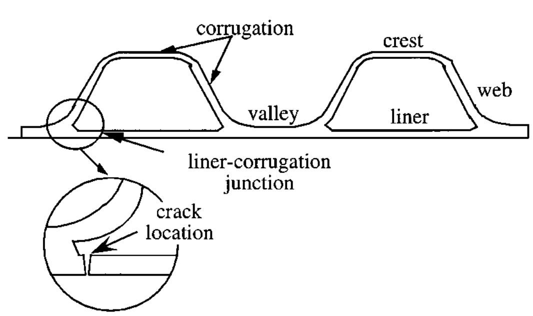

Figure 2. Schematic diagram illustrating the location of circumferential cracking in Type S pipes.

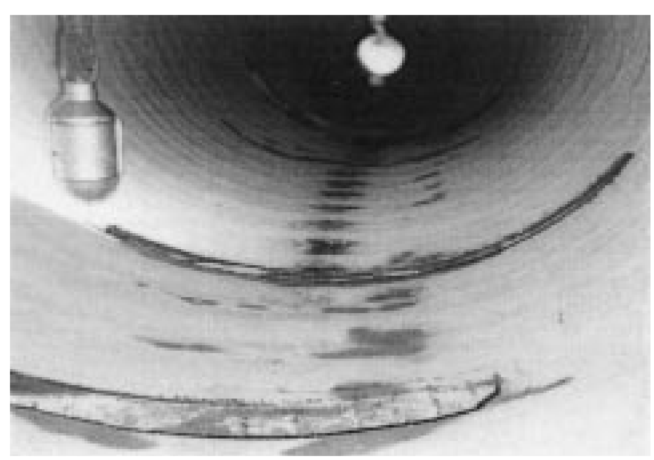

Figure 3. Illustration of the sampling method used on the cracked area of a liner.

TABLE 7 Information on the commercially available new pipe samples

Sample	Pipe Producer	Diameter (mm)	Profile	Resin Composition
1	I	460	Type S – annular	100% virgin resin (VR-1)
2	I	460	Type S – annular	Blended resin – reprocessed resin (RR-1)/ postconsumer resin (PCR-1)
3	I	460	Type S – annular	Blended resin – (VR-1/RR-1/PCR-1)
4	II	600	Type S – annular	100% virgin resin (VR-2)
5	III	600	Type S – annular	Blended resin – two virgin resins (VR-3/VR-4)
6	III	600	Type S – annular	Blended resin – (VR-3/PCR-2)
7	IV	600	Type S – annular	100% virgin resin (VR-5)
8	II	600	Type S – helical	100% virgin resin (VR-6)
9	I	600	Type S – annular	100% virgin resin (VR-7)
10	II	900	Type S – annular	100% virgin resin (VR-2)
11	IV	900	Type S – annular	100% virgin resin (VR-8)
12	I	900	Type S – annular	100% virgin resin (VR-1)
13	I	1220	Type S – annular	100% virgin resin (VR-1)
14	II	1220	Type S – honeycomb	100% virgin resin (VR-9)

Note: Type S – This type of pipe has a full circular cross-section with an outer corrugated pipe wall and a smooth inner liner. Corrugation may be either annular or helical.
Virgin resin (VR) = material in the form of pellets, granules, powders, floc, or liquid that has not been subject to use or processing other than that required for its initial manufacture.
Reprocessed resin (RP) = regrind or recycled-regrind material that has been processed for reuse by extruding and forming into pellets or by other appropriate treatment. (The reprocessed resins typically are not in-house material but are sold by other manufacturers that make different types of products.)
Postconsumer resin (PCR) = materials generated by a business or consumer that have served their intended end use and that have been separated or diverted from solid waste for the purpose of collection, recycling, and disposition.

made from each type of resin and pipe sample. Specimens were taken from these plaques for various types of testing.

Material Properties

The material properties listed in Table 8 were evaluated on both compression molded plaques and pipe materials. Test procedures and data are included in Appendix D, which is not published herein. Results of the tests are summarized in this section, along with the corresponding required value defined in the M 294 Specification.

Density. In general, the density of a polymer correlates directly to the percentage of crystallinity; that is, a high density reflects a high percentage of crystallinity. The density test was performed according to the density gradient method, ASTM D 1505. The test data are included as Appendix D-1. For materials containing carbon black, the resin density was calculated using Equation 1, as described in ASTM D 3350.

$$D_r = D_p - 0.0044(C) \quad (1)$$

where

TABLE 8 Tests being performed on pipe resins or wall materials

Sample	Test	ASTM Method	Property Measured
Plaques made from: resin pellets or pipe pieces	Density (ρ)	D 1505	Crystallinity
	Melt Index (MI)	D 1238	Related to molecular weight
	Flexural Modulus (FM)	D 790	Flexural strength
	Tensile Yield Strength (σ_y)	D 638	Tensile strength limit
	ESCR	D 1693	Slow crack growth
	NCTL	D 5397	Slow crack growth
	Carbon black content	D 4218	Carbon black weight content
	OIT	D 3895	Related to antioxidant content
Pipe walls	Density (ρ)	D 1505	Crystallinity
	NCTL	D 5397	Slow crack growth

Note: ESCR = environmental stress crack resistance
NCTL = notched constant tensile load test
OIT = oxidative induction time

D_r = density of resin
D_p = density of pigmented product
C = percentage of carbon black content

For pipes that were made from a single resin, similar density values were obtained on plaques made from both resin pellets and pipe pieces. Of the 14 tested pipe samples, 13 had an average density value within the M 294 Specification, which requires a density between 0.945 and 0.955 g/cm^3, as indicated in Figure 4. The only exception was Sample 2, which was made from blending reprocessed resin with post-consumer resin. Its density value was slightly above the defined upper limit. Comparing the density between plaques of pipe pieces and pipe wall materials, the pipe wall materials generally had slightly lower density values than the plaques. This indicated a greater percentage of amorphous phase material (i.e., lower crystallinity) present in the pipe relative to the plaques. This suggests that the pipe was probably cooled at a faster rate during production than the 15°C/min that was used in making the plaque.

Carbon black content. Carbon black is added to the resin formulation to provide ultraviolet (UV) resistance. The pipe is only vulnerable to UV light during the storage period and before backfilling. Once the pipe is covered by soil, it is not subjected to ultraviolet light. Accorsi and Romero (*6*) stated that up to the level of opacity, in general the higher the loading of carbon black, the greater the degree of ultraviolet light stability. The addition of carbon black above the opacity level (which is around 3%) does not provide significant improvement on the ultraviolet resistance. Furthermore, a strong synergistic effect exists between carbon black and antioxidants (*7*). The UV resistance of the pipe must be evaluated under a carefully designed experimental program with known types of carbon black and antioxidant packages.

The amount of carbon black in pipe materials was determined using the ASTM D 4218 test procedure. The test data are included as Appendix D-1. The average value was used in the calculation of the corresponding resin density as explained in the density section. The average weight percentage of carbon black in the 14 tested pipe samples ranged from 0.09% to 3.2%. Eight samples had a carbon black content less than the minimum specified value of 2%, as shown in Figure 5.

Melt index. The melt index (MI) value provides information regarding the melt flow behavior of the polymer, which is important to the extrusion process of manufacturing polymer pipes. Additionally, the MI value is empirically related to the molecular weight of the resin. For the same type of polymer, with a similar molecular weight distribution, a high MI value indicates a low molecular weight and vice versa. Note that this relationship is not applicable to blended polymers that possess double peaks in the molecular weight distribution curve.

The MI test was performed according to ASTM D 1238. Two conditions were evaluated: $M_{2.16}$ (190°C at 2.16 kg) and $M_{21.6}$ (190°C at 21.6 kg). Note that the ASTM D 3350 (i.e., M 294 Specification) requires only the former condition (190°C at 2.16 kg). The two tests were conducted so as to calculate a flow rate ratio (FRR) value, which provides insight into the molecular weight distribution of the polymer. The individual and average values of the two MI tests and the corresponding FRR values of 14 pipe materials are included as Appendix D-2. Comparing the $M_{2.16}$ values of resin pellets with pipe pieces for the same material, their difference was around 0.1 g/10 min or less. This difference was probably due to the variability within a manufacturer's production lot of resin. Samples 2 and 14 had a MI value slightly higher than the M 294 maximum specified value of 0.4 g/10 min, as depicted in Figure 6.

The majority of the tested pipes exhibited a FRR value in the range of 90 to 100, as exhibited in Figure 7. The exceptions were Samples 8, 9, and 11, which consisted of relatively higher FRR values than the others, indicating a broader molecular weight distribution curve. Sample 8, a helical pipe, had the highest FRR value and the lowest $M_{2.16}$ value. The low $M_{2.16}$ value suggests that this material was composed of a greater fraction of high molecular weight polymers, whereas

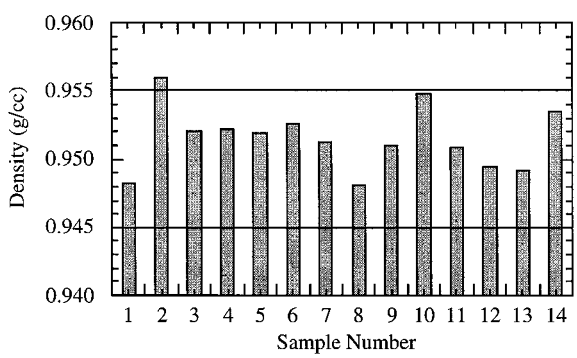

Figure 4. Density data of 14 commercially available new pipe samples. (The two horizontal lines represent the M 294 specified limits.)

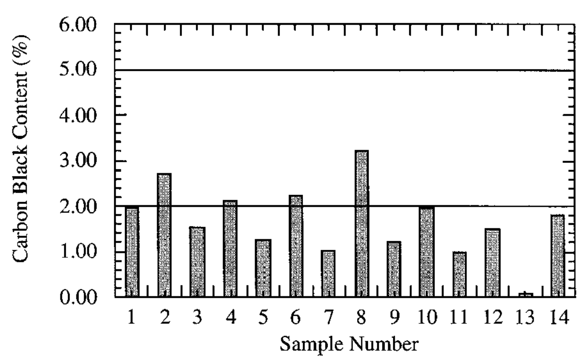

Figure 5. Carbon black content of 14 commercially available new pipe samples. (The two horizontal lines represent the M 294 specified limits.)

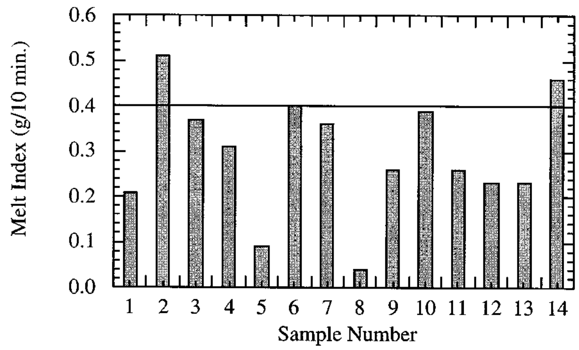

Figure 6. MI data of 14 commercially available new pipe samples. (The horizontal line represents the M 294 specified upper limit.)

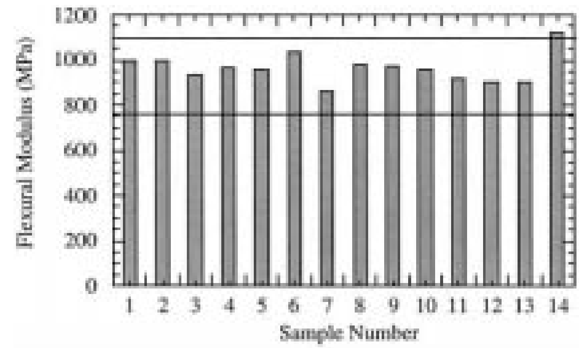

Figure 8. Two percent flexural modulus data of 14 commercially available new pipe samples. (The two horizontal lines represent the M 294 specified range.)

the high FRR value reflects a broad molecular weight distribution, which assists in the processing of the pipe.

Flexural modulus. This test was performed according to ASTM D 790 and ASTM D 3350 test procedures. The average flexural modulus at 2% strain and the standard deviation are included as Appendix D-3. All tested materials complied with the M 294 requirement; their values were either within or above the defined cell class, as indicated in Figure 8.

Tensile yield strength. The tensile yield stress was evaluated in accordance with ASTM D 638-Type IV with a crosshead speed of 50 mm/min. The yield stress and breaking elongation of each material were recorded. The data are included as Appendix D-4. Note that ASTM D 3350 does not specify breaking elongation; however, this property is believed to be related to SCR. The yield strength of the pipe materials was either within or above the M 294 requirement, as shown in Figure 9.

In each material, the breaking elongation was consistently lower in plaques made from the pipe pieces than in plaques made from the corresponding resin pellets. In addition, a relatively high standard deviation was associated with data obtained from the pipe pieces. The low breaking elongation and scattering of the data may have been caused by microscopic interfacial boundaries between the pipe pieces. Such scattering impeded the comparison between the breaking elongation and the SCR property.

Environmental stress crack resistance. Based on the current ASTM D 3350 Specification, the SCR property of the polyethylene pipe material should be evaluated according to ASTM D 1693, Condition B. The test is conducted using ten notched specimens, which are bent and immersed in 10% Igepal at 50°C. Test specimens were taken from plaques made from either resin pellets or pipe pieces. Table 9 shows the pass/fail criteria according to the M 294 Specification, which allows a maximum of 50% failures after a 24-hr testing duration. (The numbers of cracked specimens and the test duration are included as Appendix D-5.) Of the 14 tested materials, Samples 2, 3, 4, 7, 9, 10, 11, and 14 failed the specification.

It should be noted that the Condition B test environment was changed from 100% Igepal to 10% Igepal in 1994. Many of the resin suppliers are still using 100% Igepal to evaluate resins used in drainage pipes. To identify the possible differ-

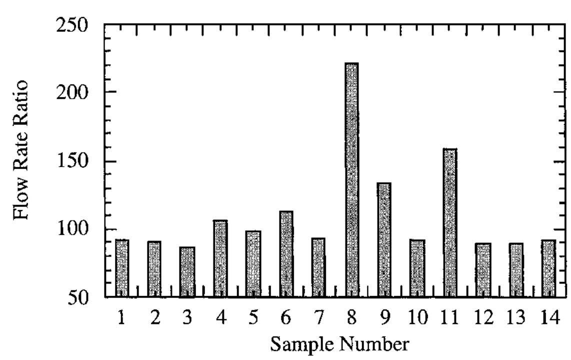

Figure 7. Flow rate ratio value of 14 commercially available new pipe samples. (There is no M 294 specified value.)

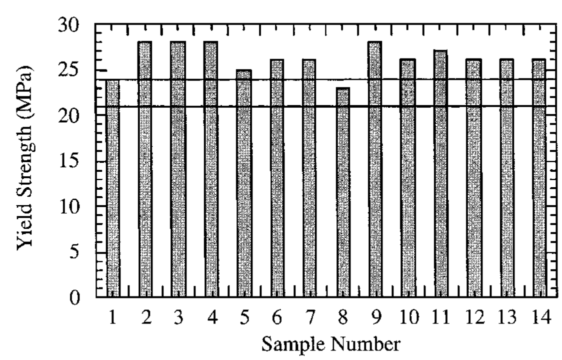

Figure 9. Yield strength data of 14 commercially available new pipe samples. (The two horizontal lines represent the M 294 specified range.)

TABLE 9 ESCR test data for commercially available new pipe materials (per M 294 Specification)

Sample	Type of Material	Results (Pass/Fail Criteria)
1	Resin Pellets	Passed
	Pipe Pieces	Passed
2	Pipe Pieces	Failed
3	Pipe Pieces	Failed
4	Resin Pellets	Failed
	Pipe Pieces	Failed
5	Pipe Pieces	Passed
6	Pipe Pieces	Passed
7	Resin Pellets	Failed
	Pipe Pieces	Failed
8	Resin Pellets	Passed
	Pipe Pieces	Passed
9	Pipe Pieces	Failed
10	Resin Pellets	Failed
	Pipe Pieces	Failed
11	Resin Pellets	Failed
	Pipe Pieces	Failed
12	Pipe Pieces	Passed
13	Pipe Pieces	Passed
14	Resin Pellets	Failed
	Pipe Pieces	Failed

ence in the test results between the two Igepal concentrations, the ESCR test was performed using 100% Igepal on some of the pipe samples. Table 10 shows the ESCR data of eight selected pipe samples in both 10% and 100% Igepal at 50°C. Although the 100% Igepal is known to be a less aggressive reagent in promoting stress cracking, the two sets of results reveal no significant differences. Only Sample 3 exhibited a pronounced difference between the two test conditions. It failed in 10% Igepal but passed in 100% Igepal solution. Samples 7 and 9 showed a slight difference between the two conditions. The data seem to suggest that for the current ESCR criteria, that is, a maximum of 50% failure after 24 hr, the concentration of the Igepal does not have a significant effect.

Oxidative induction time. Oxidative induction time (OIT) is defined in ASTM D 3895 as "a relative measure of a material's resistance to oxidative decomposition; it is determined by the thermal analytical measurement of the time interval to the onset of an exothermic oxidation of a material at a specified temperature in an oxygen atmosphere." For the same type of antioxidant formulation, the OIT indicates the total amount of antioxidant present in the specimen (*8*). However, OIT does not reflect the individual type or the amount of each antioxidant present in the formulation. It must be emphasized that comparisons between different antioxidant packages should be carried out with great caution. Nevertheless, results from a long-term aging study have indicated that the mechanical properties of the material remain essentially unchanged until all antioxidants are depleted (*9*).

It should be recognized that the purpose of the OIT test in this project was not to predict the longevity of the material, because different manufacturers probably use different antioxidant formulations. The objective was to measure the OIT of the field retrieved pipes to ensure that property degradation had not taken place at the time the sample was collected. In addition, OIT tests on commercially available new pipe samples can provide some insight regarding the average amount of antioxidant being used. By comparing the overall OIT value from the new and field retrieved pipes, the consumption of antioxidants during the service time can be estimated.

TABLE 10 ESCR test results under two different reagent concentrations

Sample	Type of Material	Result	
		10% Igepal at 50°C	100% Igepal at 50°C
		number of cracked specimens in 24 hours	number of cracked specimens in 24 hours
1	Resin Pellets	none	nt
	Pipe Pieces	none	nt
2	Pipe Pieces	10 (all failed after 14 hours)	10 (all failed after 15 hours)
3	Pipe Pieces	10 (all failed after 19 hours)	3 (3 failed after 24 hours)
4	Resin Pellets	10 (6 failed after 13 hours)	nt
	Pipe Pieces	10 (7 failed after 12 hours)	10 (all failed after 17 hours)
5	Pipe Pieces	none	nt
6	Pipe Pieces	none	nt
7	Resin Pellets	10 (all failed after 20 hours)	nt
	Pipe Pieces	10 (all failed after 16 hours)	10 (5 failed after 20 hours)
8	Resin Pellets	none	nt
	Pipe Pieces	none	nt
9	Pipe Pieces	10 (all failed after 21 hours)	8 (8 failed after 24 hours)
10	Resin Pellets	10 (8 failed after 13 hours)	nt
	Pipe Pieces	10 (7 failed after 15 hours)	10 (9 failed after 17 hours)
11	Resin Pellets	10 (all failed after 20 hours)	nt
	Pipe Pieces	10 (all failed after 20 hours)	10 (all failed after 24 hours)
12	Pipe Pieces	none	nt
13	Pipe Pieces	none	nt
14	Resin Pellets	10 (7 failed after 8 hours)	nt
	Pipe Pieces	10 (8 failed after 10 hours)	10 (8 failed after 8 hours)

Note: nt = not tested

The OIT test was performed according to ASTM D 3895. This test is used to determine the total amount of antioxidants present in the material. Figure 10 shows the average OIT values obtained from plaques made from resin pellets and pipe pieces, as well as pipe wall materials. The individual test data are included as Appendix D-6. The average OIT values obtained from the plaque and wall materials were very similar in most of the samples, except Sample 3, which contained PCR. The average OIT value for the tested samples varied from 1 to 45 min. The wide range of OIT values indicates that many different antioxidant formulations are being used in these 14 commercially available new pipes.

The OIT test is not a required parameter in ASTM D 3350; thus, no specification value is established. However, a thermal stability test, oxidative induction temperature, is included in the ASTM standard to ensure the stabilization of the polymer during the pipe extrusion process. The test is only applicable to evaluating the unprocessed resin pellets, not the finished product. In addition, the test cannot provide information on the long-term performance of the pipe (*10*).

Notched Constant Tensile Load Test

Although the SP-NCTL test was the objective of this project, the full (F-NCTL) test and partial (P-NCTL) test were used to evaluate the SCR of pipe materials. Results of the P-NCTL tests are then used to define the condition of the SP-NCTL test so that the SCR of different pipe materials could be compared. Also, the selected test condition of SP-NCTL test has been included in the recommended specification.

F-NCTL tests. From the 14 pipe samples, Samples 1, 9, and 14 were selected for evaluation by the F-NCTL test to demonstrate the ductile-to-brittle transition behavior. Test specimens were taken from five 1.8-mm-thick plaques, which were made of resin pellets. Tests were performed using applied stresses ranging from 10% to 50% of the yield stress of the material. Three specimens were tested at each stress level. At stress levels below 25%, five specimens were tested. The notch depth in all test specimens was 0.36 mm, which equals 20% of the nominal thickness. The applied stress was calculated based on the remaining ligament cross-sectional area. The test data are presented in graphic form by plotting the percentage of yield stress against failure time on a log-log scale. The reason for selecting percentage of yield stress over applied stress was that pipes with different yield stress values, as indicated in Figure 9, induced different stress values on the pipe wall under the same strain value. A pipe with a high yield stress resulted in a lower stress value than that with a low yield stress. The percentage of yield stress minimized the effect of yield stress and provided a fair comparison between different resins.

For Sample 1, 12 applied stresses were tested, ranging from 15% to 50% of the yield stress of the material. The failure time at each applied stress was recorded to an accuracy of 0.01 hr. Figure 11 shows the F-NCTL test response curve. The curve consists of two linear regions. In the high applied stress region, specimens failed predominantly in the ductile mode. This region of the curve is called the ductile region. The slope of this portion of the curve is relatively shallow. In contrast, in the low applied stress region, specimens failed in a brittle mode. This region of the curve is called the brittle region. The slope of the curve becomes much steeper than that of the ductile region. For this material, the ductile-to-brittle transition occurred at 35% yield stress with a transition time of 8.8 hours. The shape of the transition region is described as a “step transition” in ASTM D 5397.

For Sample 9, 11 applied stresses were tested, ranging from 15% to 50% of the yield stress of the material. Figure 12 shows the F-NCTL test response curve, which again consists of two linear portions. The transition occurred at 45% yield stress and 0.5 hr. The shape of the transition is defined as a “knee transition” in the standard.

For Sample 14, 12 applied stresses were tested, ranging from 10% to 50% of the yield stress of the material. Figure 13 shows the F-NCTL test response curve. The transition occurred at 40% yield stress and 0.5 hours. The shape of the transition is defined as a “knee transition” in the standard.

The ductile-to-brittle transition observed in these three F-NCTL test response curves indicates that brittle failure can take place in pipes made from this material.

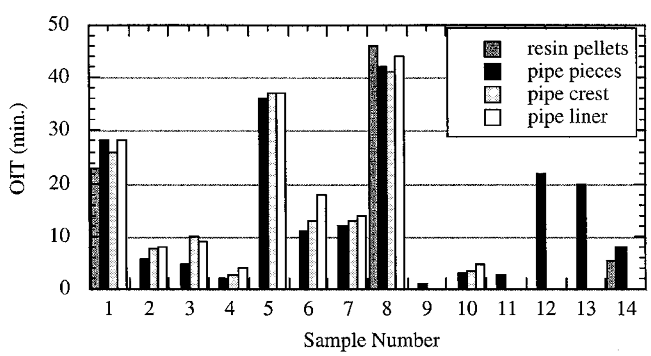

Figure 10. OIT data of 14 commercially available new pipe samples. (There is no M 294 specified value for this property.)

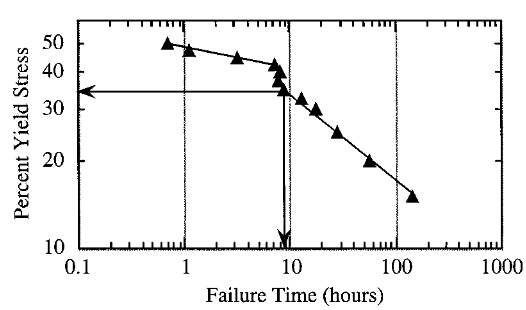

Figure 11. The response curve of the F-NCTL test for Sample 1.

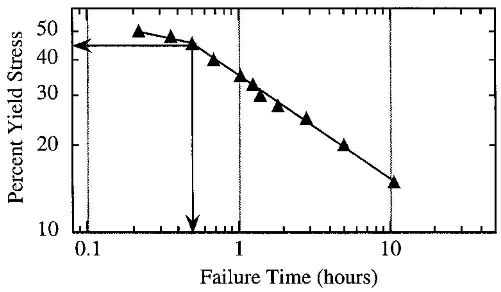

Figure 12. The response curve of the F-NCTL test for Sample 9.

P-NCTL tests. The P-NCTL test is an abbreviated version of the F-NCTL test. The test focused only in the brittle region of the curve, because this was the region of primary interest. Three to four applied stresses were selected in the brittle region of the full curve. The stress levels vary from 10% to 25% of the yield stress of the material. Five specimens were tested at each stress level and an average value was reported. The failure time of each specimen was recorded to an accuracy of 0.1 hr instead of 0.01 hr. All 14 available pipe samples were evaluated. The data are presented by plotting percent yield stress against failure time on a log-log scale.

No significant difference in failure time existed between plaques made from resin pellets and pipe pieces. (The test data and response curves of the P-NCTL test obtained from plaques that were made from resin pellets and pipe pieces are included as Appendix E, which is not published herein.) The following conclusions are drawn regarding all commercially available new pipe samples:

- The cutting and remolding of pipe pieces into plaques does not substantially alter the SCR of the original resin. Hence, the SCR property of the resin can be evaluated using plaques made from the finished pipe product.
- The addition of carbon black does not seem to influence the SCR property of these resins.

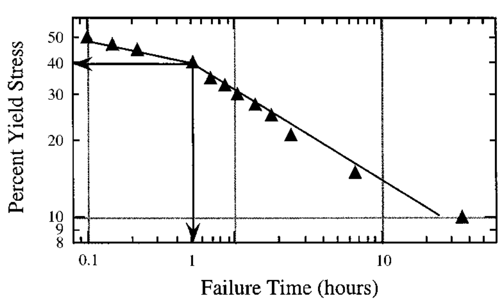

Figure 13. The response curve of the F-NCTL test for Sample 14.

- The SCR analysis for all new and field pipe samples will be based on the P-NCTL test results obtained from plaques made from pipe pieces so that direct comparison can be made between them.
- The P-NCTL test results of the 14 commercially available new pipe samples are presented in Figures 14(a) and 14(b). Figure 14(a) shows the results obtained from Samples 1 through 7, and Figure 14(b) shows the results obtained from Samples 8 through 14. A linear relationship was obtained between applied stress and failure time in the majority of the samples, except Samples 3, 7, and 11. In those three samples, the linear relationship ceased to exist at 10% yield stress. The failure time at 10% stress was longer than the projected value.

The linear relationship between the applied stress and failure time can be expressed by the power law, as indicated in Equation 2. The slope of the lines is fairly similar in the 14 samples, as shown in Table 10. The average slope value is 0.34 ± 0.07.

$$S = A * t^m \quad (2)$$

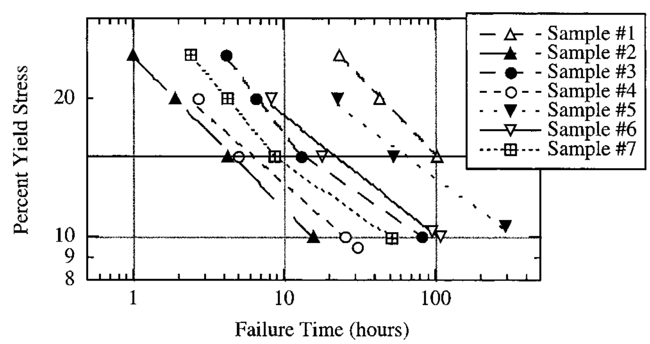

Figure 14(a). Response curves of the P-NCTL test for Samples 1 through 7.

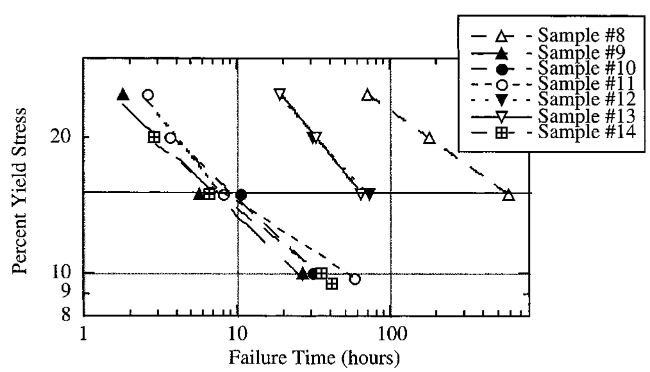

Figure 14(b). Response curves of the P-NCTL test for Samples 8 through 14.

where

S (% (σ_y or MPa)) = yield stress
t (hr) = failure time
m = slope of the line
A = constant (related to material and test environment)

On the basis of these 14 sets of data, it appeared that the applied stress at 10% yield stress was not appropriate for the SP-NCTL test, because the linear relationship was not valid at this stress level for all materials. To avoid the uncertainty, an applied stress at 15% yield stress was selected to compare SCR between the materials. Furthermore, the use of a higher stress level allowed the test to be completed in a shorter period of time, a feature that is believed to be important for a quality control test. (Note that the SP-NCTL test procedure is included as the Appendix to ASTM D 5397; however, few modifications were required to adopt the standard for testing HDPE corrugated pipe materials.)

The failure times of the 14 pipe samples at this 15% yield stress are listed in Table 11. Figure 15 illustrates graphically the failure times of 14 tested pipe samples at this particular stress; their failure times ranged from 5 hr to 600 hr. Nine of the 14 samples had failure times less than 20 hr. Four samples had failure times that ranged from 60 to 100 hr, and one sample had a failure time greater than 100 hr. The sample with a failure time greater than 100 hr had a helical pipe profile. The large difference in failure times demonstrates the effectiveness of the SP-NCTL test in identifying the SCR of different HDPE pipe materials.

Fracture morphology. The fracture morphology of failed NCTL test specimens at different stress levels was examined using a scanning electron microscope. Specimens from pipe Sample 14 were evaluated. The specimen failing at 50% yield stress was selected to illustrate the ductile failure, as shown in Figure 16. The specimen failing at 45% yield stress

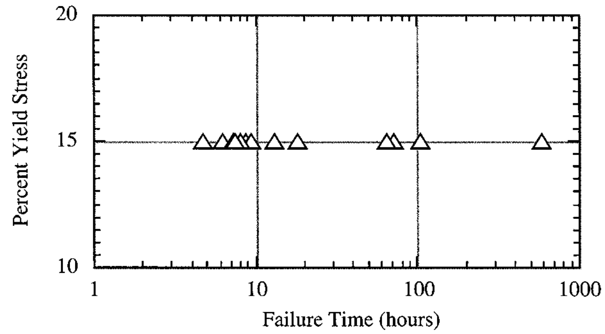

Figure 15. Failure times at 15% yield stress of 14 commercially available new pipes, which illustrate the vast difference in the SCR of the resins used in the HDPE corrugated pipes. (Note: Samples 5 and 13 have the same failure time. Thus, only 13 points appear on the graph.)

was selected to illustrate the failure morphology at the transition region, as shown in Figure 17. The other three specimens failing at 10%, 15%, and 20% yield stress were selected to illustrate the effect of applied stress on the brittle fracture morphology, as shown in Figures 18 through 20. A close view of the microstructure at location “A” in each of the three brittle failed specimens is depicted in Figures 21 through 23. The needle-like structure, called “fibrous,” resulted from a slow crack-growth failure. The size of the fibrous structure changed with the applied stress; a higher applied stress was associated with a larger fibrous structure. Also, on each fracture surface, the size of the fibrous structure increased as the crack propagates (i.e., it increases with stress).

The fracture morphology is a very useful forensic tool. In this study, the fibrous morphology was used as a “signature” to verify whether cracking was caused by a slow crack-growth mechanism or by some other phenomenon. The fracture morphology of all field cracked samples was examined to identify their failure mode.

TABLE 11 Slope and failure times at 15% yield stress for 14 commercially available new pipes

Sample	Slope	Failure Time at 15% σ_y(hour)
1	- 0.34	104
2	- 0.33	4.7
3	- 0.44	13
4	- 0.29	6.2
5	- 0.24	64
6	- 0.26	18
7	- 0.40	8.6
8	- 0.24	580
9	- 0.33	7.2
10	- 0.32	9.2
11	- 0.43	8.1
12	- 0.38	71
13	- 0.42	64
14	- 0.27	7.5

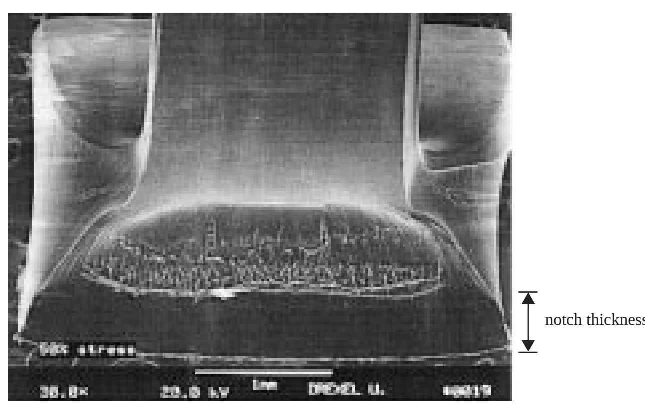

Figure 16. Fracture surface of a specimen failing at 50% yield stress, illustrating ductile failure.

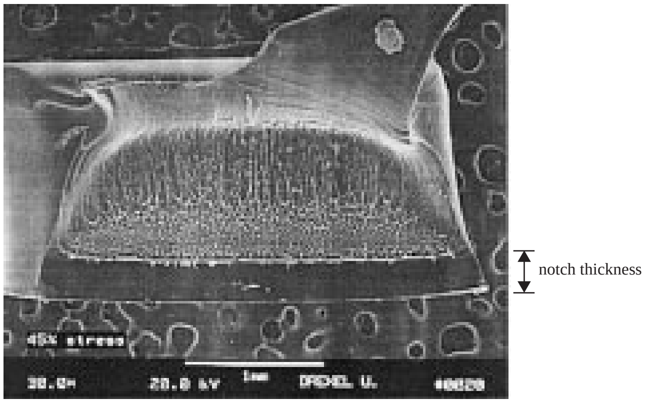

Figure 17. *Fracture surface of a specimen failing at 45% yield stress, illustrating transition behavior between ductile and brittle failures.*

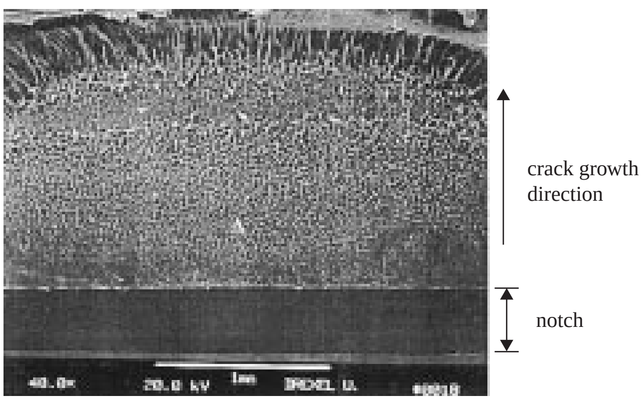

Figure 18. *General view of the fracture surface of a specimen at 20% yield stress, illustrating brittle failure.*

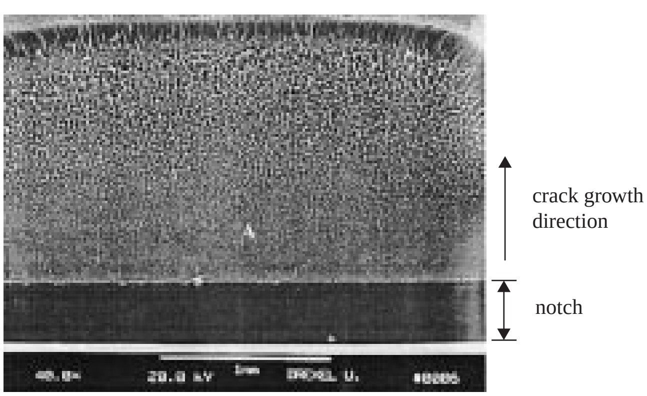

Figure 19. *General view of the fracture surface of a specimen at 15% yield stress, illustrating brittle failure.*

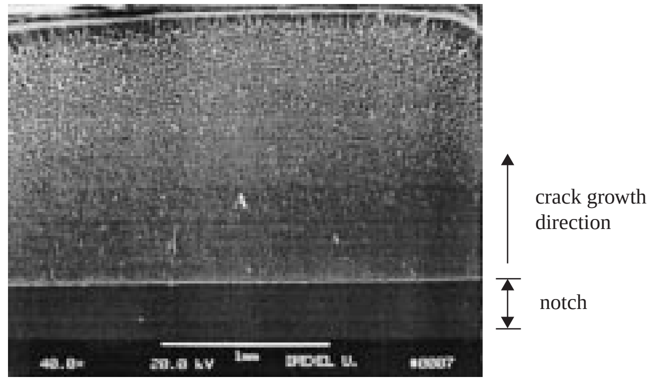

Figure 20. *General view of the fracture surface of a specimen at 10% yield stress, illustrating brittle failure.*

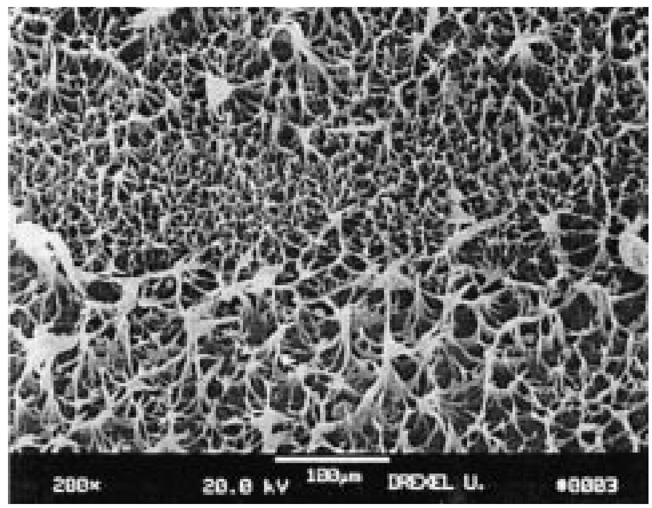

Figure 21. *Detail view of the fibrous structure of a specimen failing at 20% yield stress (at location A of Figure 18).*

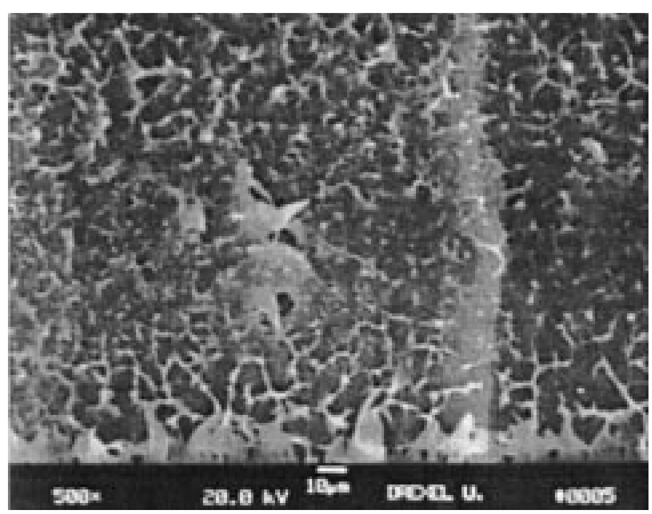

Figure 22. *Detail view of the fibrous structure of a specimen failing at 15% yield stress (at location A of Figure 19).*

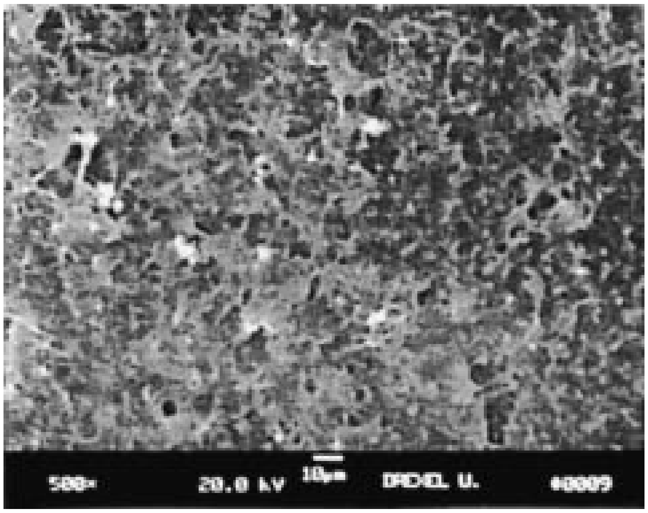

Figure 23. Detail view of the fibrous structure of a specimen failing at 10% yield stress (at location A of Figure 20).

Laboratory Results of Commercially Available New Pipes

The various material properties along with the SP-NCTL test results of the 14 pipe samples are shown in Table 12, together with values defined in the M 294 Specification. The density, flexural modulus, and yield strength of the 14 commercially available new pipes largely complied with the current specification. The only exception was the density of Sample 2, which was slightly higher than the specified value of 0.955 g/cm^3. Regarding MI, two of the samples, Samples 2 and 14, had values above the upper specified value of 0.4 g/10 min. For SCR, 8 of the 14 samples failed to pass the specified criterion. In contrast, the failure times of the SP-NCTL test at 15% yield stress showed a specific value, from 5 to 600 hr. While a correlation between the SP-NCTL test and the ESCR test was observed, the quantified value is of far greater significance. Samples with failure times less than 14 hr in the SP-NCTL test failed the current ESCR test specification. The overall test results suggest that resin materials that comply with basic material specifications, such as density, MI, flexural modulus, and yield strength, can exhibit diverse SCRs.

As far as the long-term properties involving carbon black content and OIT values are concerned, most of the samples contained greater than 1% carbon black but less than 3%,

TABLE 12 The cell class data based on ASTM D 3350 of 14 commercially available new pipes

Sample	Property						
	Density[1] (D1505) (g/cc)	MI[2] (D1238) (g/10 min.)	Flexural Modulus (D790) (MPa)	Yield Strength (D638) (MPa)	OIT[3] (D3895) (min.)	ESCR[4] (D1693)	SP-NCTL[5] (15%) (D5397) (hours)
M 294 spec.	**3** 0.945-0.955	**3** 0.4 to 0.15	**5** 758 to 1103	**4** 21 to 24	NA	**2** Cond. B 50%/24 hr	NA
1	0.9483	0.21	998	24	28	passed	104
2	0.9560	0.51	995	28	6	failed	4.7
3	0.9520	0.37	934	28	5	failed	13
4	0.9521	0.31	969	28	2	failed	6.2
5	0.9519	0.09	954	25	36	passed	64
6	0.9525	0.40	1038	26	11	passed	18
7	0.9512	0.36	867	26	12	failed	8.6
8	0.9481	0.04	977	23	42	passed	580
9	0.9510	0.26	970	28	1	failed	7.2
10	0.9548	0.39	954	26	3	failed	9.2
11	0.9508	0.26	921	27	3	failed	8.1
12	0.9494	0.23	900	26	22	passed	71
13	0.9492	0.23	905	26	20	passed	64
14	0.9535	0.46	1123	26	8	failed	7.5

carbon black varies from 1% to 3%, except Sample #13 which contains 0.09%.

NA = non-applicable
1 Calculated resin density values
2 MI = melt index
3 OIT = oxidative induction time
4 ESCR = environmental stress crack resistance (criteria 24 hour/50% failure)
5 SP-NCTL = single-point notched constant tensile load

whereas OIT values varied from 1 min to 42 min. For pipe that is exposed to sunlight, both carbon black and antioxidants are important in protecting the material from degradation, because a synergistic effect takes place between these two additives. On the other hand, in buried applications, antioxidants are the essential substance protecting the material from degradation. However, the minimum required amount of carbon black and antioxidants that can ensure the service lifetime of the pipe is a complete research project in itself. Published information on HDPE pressure pipes and HDPE geomembranes can serve as guidelines for possible future research (*11*, *12*).

Regarding pipe samples that contained either reprocessed resin or postconsumer resin, most of their properties were within the specified material values. For example, Sample 6, which was made from blending virgin resin with postconsumer resin, complied with all current specification requirements. Thus, reprocessed resins and postconsumer resins can also be used for corrugated pipe applications, as long as the final blended product fulfills the required specification.

EVALUATION OF RETRIEVED PIPE SAMPLES

As stated in the Field Investigations section of this report, 29 field sites were investigated, as recorded in Table 5, while 23 cracked pipe samples were retrieved from 20 of the sites, and 17 cracked samples were selected for evaluation. In addition, samples were taken from two uncracked pipes that had service lifetimes of 8 and 12 years. These two pipes exhibited no cracking in spite of large deflections. Table 13 lists 19 selected field samples. Detailed descriptions of each field site and pipe condition are presented in the site summary report, Appendix F, which is not published herein.

Fracture Morphology

One of the important investigations on the retrieved pipe samples was to determine the type of failure mechanism that caused cracking. This was achieved by examining the fracture morphology of the crack surfaces, which provided information on the cracking mechanism, crack initiation, and crack-growth direction. The typical fracture morphology as observed in a scanning electron microscope in each of the field samples is summarized in Table 14. The majority of the crack surfaces exhibited a fibrous structure, as shown in Figure 24, which was similar to that observed in failed P-NCTL test specimens (Figures 17 through 20). This indicates that cracks in those pipes failed via a slow crack-growth mechanism. However, Sites B, G, V, and W were exceptions. The fracture surface of cracked pipes in these four sites showed a flake structure, as revealed in Figure 25. The flake morphology was not generated by the slow-crack growth mechanism, but rather by a rapid crack-propagation mechanism that is typically associated with a dynamic force and cold temperature (*13*). A similar type of failure is occasionally detected in exposed HDPE pressure pipes and geomembranes when

TABLE 13 Pipe conditions at 19 selected field sites

Site	Type	Age (years)	Deflection				Buckling	Longitudinal Bending	Cracking
			Horizontal		Vertical				
			min.	max.	min.	max.			
A	C-Helical	16	7.3%	8.3%	-6.3%	-12.5%	No	No	Circumferential/Longitudinal
B	C-Helical	13	N/A	N/A	N/A	N/A	No	Yes	Circumferential
D[1]	C-Annular	2	N/A	N/A	N/A	N/A	No	No	Longitudinal
E	S-Honeycomb	3	-1.3%	5.1%	-3.3%	-10.0%	Yes	No	Circumferential/Longitudinal
F	S-Helical	<1	1.8%	10.3%	-5.1%	-19.4%	Yes	No	Circumferential/Longitudinal
G	S-Annular	1	3.3%	5.3%	-3.5%	-5.7%	No	No	Circumferential
H	S-Helical	4	1.3%	6.7%	-2.1%	-2.1%	No	Yes	Circumferential
I	S-Annular	1	N/A	4.2%	N/A	-4.2%	No	Yes	Circumferential
J1[2]	S-Helical	7	N/A	N/A	N/A	-25.0%	No	No	Circumferential
J2[2]	S-Annular	7	N/A	N/A	N/A	-3.3%	No	No	Circumferential/Longitudinal
K	S-Helical	6	8.3%	13.9%	-11.1%	-16.7%	Yes	No	Circumferential
L	C-Helical	8	N/A	N/A	N/A	-16.7%	Unknown	Unknown	No Crack**
N	C-Helical	12	N/A	N/A	N/A	-10.0%	Unknown	Unknown	No Crack**
O	C-Helical	10	N/A	0.4%	N/A	-4.2%	Yes	No	Circumferential
	S-Helical	10	N/A	1.3%	N/A	-4.5%	Yes	No	Circumferential
P	S-Annular	3	1.7%	5.0%	-8.3%	-5.0%	No	No	Circumferential
R	S-Helical	3	-1.4%	13.9%	-2.8%	-16.7%	No	Yes	Circumferential
U	S-Honeycomb	2	2.4%	9.5%	-7.1%	-20.2%	Yes	No	Circumferential/Longitudinal
V	S-Helical	3	No Deflections Observed				No	No	Circumferential
W	S-Honeycomb	1	1.0%	3.1%	-6.3%	-10.4%	Yes	No	Circumferential/Longitudinal

* Ages are reported as the age at the time of inspection.
** Information was provided by the local pipe manufacturer.
A negative deflection value represents a shortening.
A positive deflection value represents an elongation.
[1] Pipe used as formwork for concrete columns.
[2] Deflection and buckling information were provided by others.
Unknown = Result of inability to enter pipe
N/A = Not Available

TABLE 14 Summary of fracture morphology in each retrieved cracked pipe

Site No.	Pipe Style	Types of Cracks	Fracture Morphology
A	C-helical	circumferential & longitudinal	fibrous structure
B	C-helical	circumferential	flake structure
D	C-annular	longitudinal	fibrous structure
E	S-honeycomb	circumferential & longitudinal	fibrous structure
F	S-helical	circumferential & longitudinal	fibrous structure
G	S-annular	circumferential	flake structure
H	S-helical	circumferential	fibrous structure
I	S-annular	circumferential	fibrous/flake structure
J-1	S-helical	circumferential	fibrous structure
J-2	S-annular	circumferential &longitudinal	fibrous structure
K	S-helical	circumferential	fibrous structure
O	C & S-helical	circumferential	fibrous structure
P	S-annular	circumferential	fibrous structure
R	S-helical	circumferential	fibrous structure
U	S-honeycomb	circumferential & longitudinal	fibrous structure
V	S-helical	circumferential	flake structure
W	S-honeycomb	circumferential & longitudinal	flake/fibrous structure

the ambient temperature falls well below freezing. The SP-NCTL test is only applicable to evaluate cracking induced by a slow crack-growth mechanism; thus, data from Sites B, G, V, and W were not included in the analysis to determine the minimum acceptable failure time.

Material Properties

Compression molded plaques were made from pieces of the retrieved pipe sections; they then were used for the evaluation of material properties and for the P-NCTL test. (For Sites E, K, P, U, V, and W, the amount of retrieved material was only sufficient to make two 1.8-mm-thick plaques; thus, the flexural modulus test was not performed.) The material properties were evaluated according to the new cell class defined in the AASHTO M 294 Specification. The test procedure used to assess each property was the same as that used for commercially available new pipes, as described in Appendix D. All data obtained from field samples are presented in Appendix D along with those from commercially available new pipes.

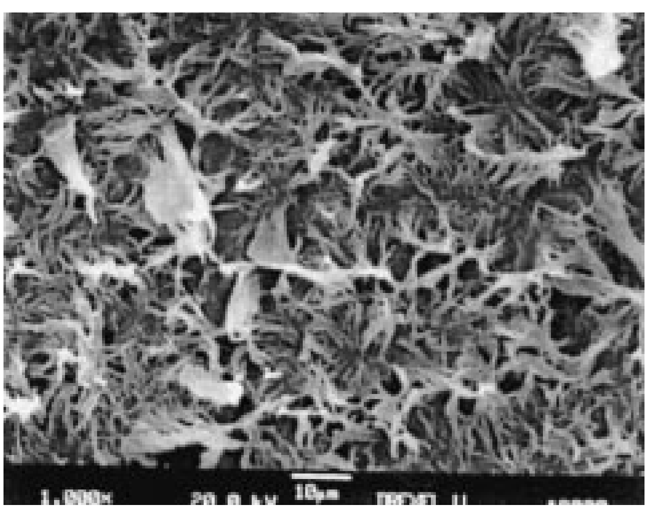

Figure 24. A typical fibrous morphology on a fracture surface of a crack (from Site H).

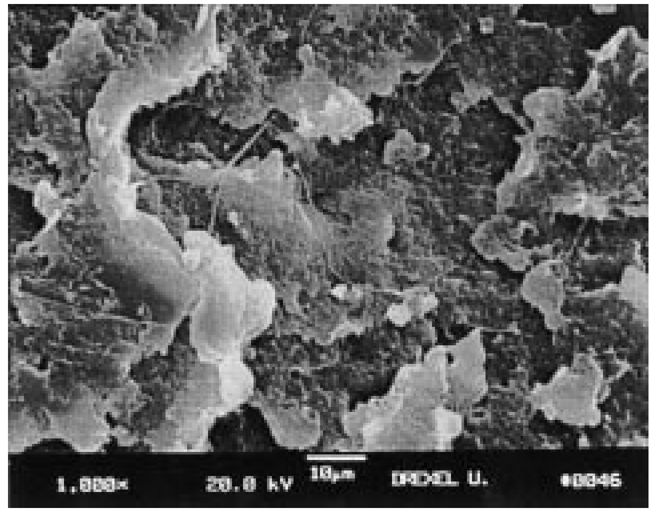

Figure 25. A typical flake morphology on a fracture surface of a crack (from Site G).

Density. As shown in Figure 26, there were three pipe samples with density values above the current specified range of 0.945 to 0.955 g/cm^3. The pipe sample from Site A had the highest density value of 0.961 g/cm^3. Such a high value suggests that the resin could be a homo-polymer rather than a co-polymer.

Carbon black content. The majority of the carbon black content in the 19 pipe samples ranged from 1 % to 3 %, as shown in Figure 27. The pipe from Site W consisted of an

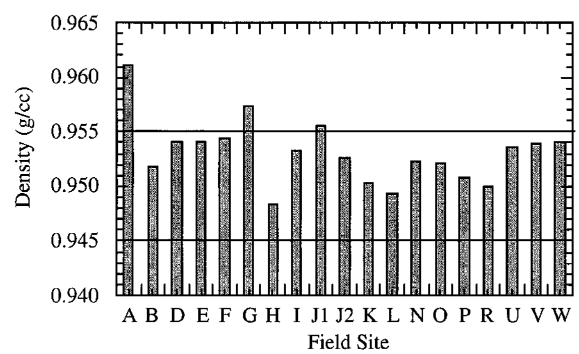

Figure 26. Density data of 19 retrieved pipe samples. (The two horizontal lines represent the M 294 specified limits.)

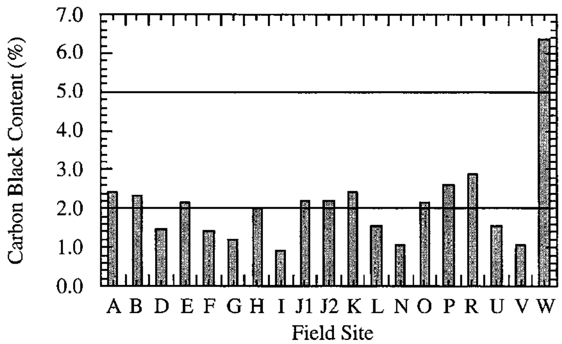

Figure 27. Carbon black content of 19 retrieved pipe samples. (The two horizontal lines represent the M 294 specified limits.)

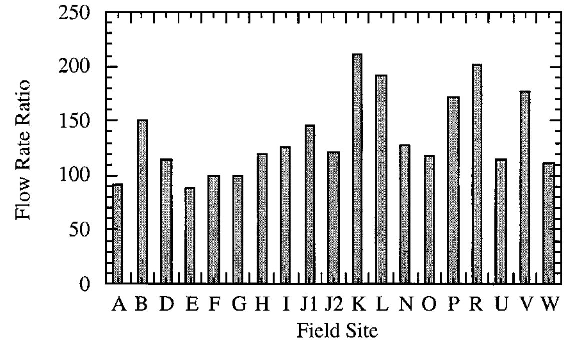

Figure 29. Flow rate ratio value of 19 retrieved pipe samples. (There is no M 294 specified value.)

unusually high carbon black content of 6.4 %, which is well above the upper specified limit of 5%.

Melt index. Pipes from Sites A and U had a MI value higher than the M 294 maximum specified value of 0.4 g/10 min, as shown in Figure 28. Seven samples, Sites J-1, K, L, N, P, R, and V had a $MI_{21.6}$ value less than 0.1 g/10 min. Figure 29 depicts the FRR value of the 19 pipe samples. The majority of the values were between 100 and 150. Pipes from Sites K, L, P, R, and V had relatively high FRR values and low $MI_{21.6}$ values.

Flexural modulus. Pipes from 13 field sites were evaluated. There was insufficient material from the other six sites. The average flexural modulus at 2% strain and the standard deviation are included in Appendix D-3 together with data from commercially available new pipes. The majority of tested materials complied with the M 294 required range between 758 and 1103 MPa, that is, their values were either within or above the defined cell class, as indicated in Figure 30. The only exception was pipe from Site L, which was below the minimum required value.

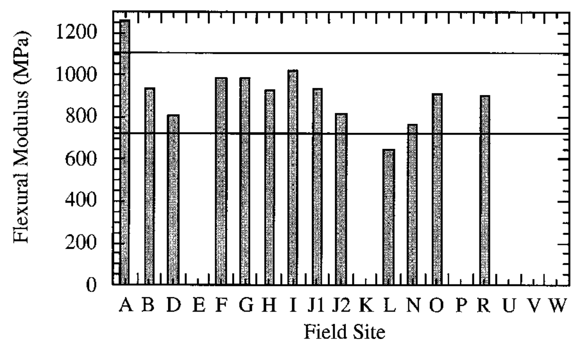

Figure 30. Two percent flexural modulus data of 13 retrieved pipe samples. (The two horizontal lines represent the M 294 specified range.)

Tensile yield strength. The yield strength of the pipe materials was either within or above the M 294 requirement, that is, between 21 and 24 MPa, as shown in Figure 31.

Environmental stress crack resistance. Table 15 shows the results of tests based on the pass/fail criteria defined in the ASTM D 3350 Specification, using ASTM D 1693. Eleven of the 19 field samples failed the test. Of the eight samples that

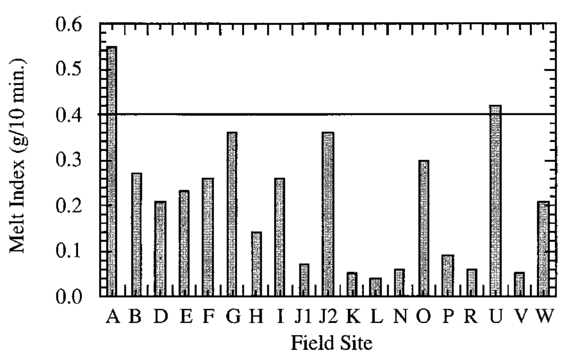

Figure 28. MI data of 19 retrieved pipe samples. (The horizontal line represents the M 294 specified upper limit.)

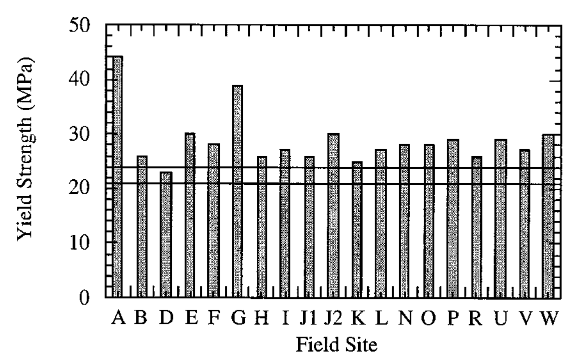

Figure 31. Yield strength data of 19 retrieved pipe samples. (The two horizontal lines represent the M 294 specified range.)

TABLE 15 ESCR test data for retrieved pipe samples (per M 294 Specification)

Sample	Type of Material	Results (Pass/Fail Criteria)
A	Pipe Pieces	Failed
B	Pipe Pieces	Failed
D	Pipe Pieces	Failed
E	Pipe Pieces	Failed
F	Pipe Pieces	Failed
G	Pipe Pieces	Failed
H	Pipe Pieces	Passed
I	Pipe Pieces	Failed
J-1	Pipe Pieces	Passed
J-2	Pipe Pieces	Failed
K	Pipe Pieces	Passed
L	Pipe Pieces	Passed
N	Pipe Pieces	Passed
O	Pipe Pieces	Failed
P	Pipe Pieces	Passed
R	Pipe Pieces	Passed
U	Pipe Pieces	Failed
V	Pipe Pieces	Passed
W	Pipe Pieces	Failed

passed the test, one had the annular profile and the others had the helical profile.

Oxidative induction time. Figure 32 shows the average OIT values obtained from plaques made from pipe pieces. The average OIT value varied from 0.2 min to 18 min. Pipes from Sites I and U had the lowest values, signifying that only an extremely small amount of antioxidants remained in these pipes.

Notched Constant Tensile Load Test

P-NCTL test was performed in all 19 retrieved pipe samples. The percent yield stress versus failure time curve is depicted in Figure 33. For the purpose of clarity, the data has been subdivided into three parts. (Complete data are included as Appendix G, which is not published herein.) Most of the pipes possessed a linear relationship between applied stress and failure time; however, a slight change in linearity was observed in pipes from Sites K, P, and W.

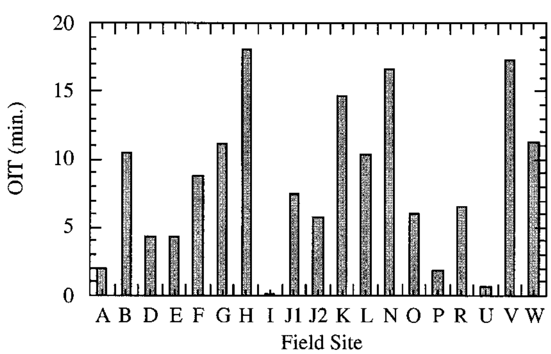

Figure 32. OIT data of 19 retrieved pipe samples. (There is no M 294 specified value.)

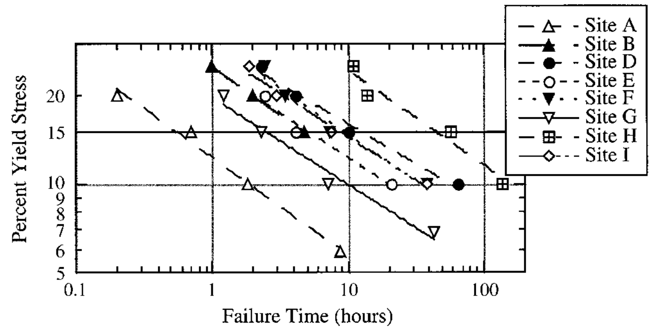

Figure 33(a). Response curves of the P-NCTL test for Sites A through I.

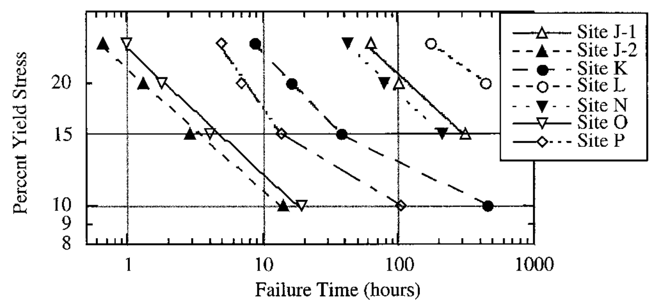

Figure 33(b). Response curves of the P-NCTL test for Sites J-1 through P.

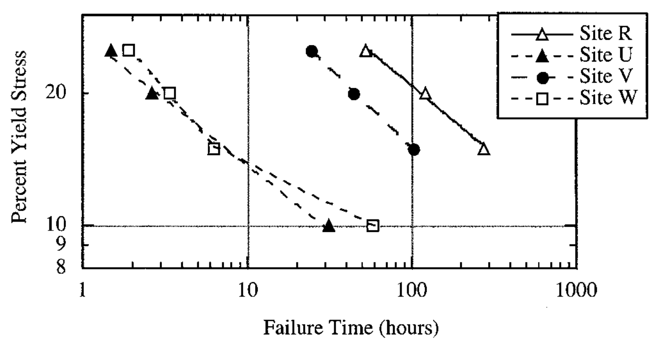

Figure 33(c). Response curves of the P-NCTL test for Sites R through W.

Table 16 lists failure times at 15% yield stress as deduced from the P-NCTL test data and the slope of the linear portion of the curves. Figure 34 shows the failure time of the 19 field pipes at 15% yield stress. The failure time values ranged from 0.5 hr to 1,800 hr. Twelve of the 19 pipes had failure times less than 15 hr. These 12 pipes had various types of pipe profiles, including helical, annular, and honeycomb. Five pipes showed a failure time greater than 100 hr, and they were all helical pipes. As with the data of Figure 15, a large difference in quantified values was seen, demonstrating the effectiveness of the test.

TABLE 16 Slope and failure times at 15% applied stress of P-NCTL test for 19 retrieved pipe samples

Sample	Slope	Failure Time at 15% σ_y(hour)
A	- 0.33	0.5
B	- 0.33	4.7
D	- 0.27	13
E	- 0.30	5
F	- 0.32	9.4
G	- 0.30	2.5
H	- 0.31	44
I	- 0.30	8.6
J-1	- 0.31	313
J-2	- 0.30	2.9
K	- 0.35	38
L	- 0.24	1800
N	- 0.32	212
O	- 0.31	4.7
P	- 0.49	14
R	- 0.31	273
U	- 0.30	6.3
V	- 0.36	102
W	- 0.43	6.3

Laboratory Results of Retrieved Pipe Samples

The material properties and the SP-NCTL test results of 19 retrieved pipe samples are shown in Table 17, together with the values defined in the M 294 Specification. Most of the retrieved pipes conformed to the current specified values, even those with service times longer than 3 years, which was before the new cell class was imposed. Pipe retrieved from Site A exhibited a high density value as well as a very high flexural modulus and yield strength. This particular pipe was probably made from a homo-polymer polyethylene resin, which generally exhibited a brittle behavior as indicated by its extremely short failure time in the SP-NCTL test. A correlation was also found between the SP-NCTL test and the ESCR test. Pipes with failure times less than 14 hr failed the ESCR criteria. This correlation was similar to that observed in commercially available new pipes.

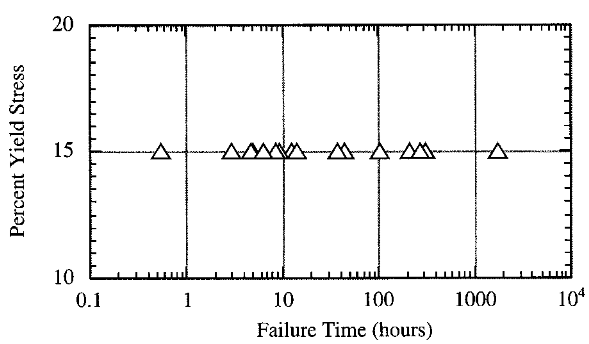

Figure 34. Failure time at 15% yield stress of 19 retrieved pipes, illustrating the vast difference in the SCR of the materials. (Note: the same failure was obtained at Sites D and P, at sites G and J-2, and at Sites U and W. Thus, only 16 points appear on the graph.)

Regarding the OIT test, Sites I and U showed a value less than 1 min, suggesting that there was almost no antioxidant present in these two pipes. Because the service time of the pipes was less than 3 years, there may have been only a limited amount of antioxidant added to the resin formulation for stabilization purposes during processing. Presently, the physical and mechanical properties of the pipes are still within specified values. It would be very informative, in regard to the long-term performance of the pipe, to continue monitoring the performance of these two pipes for the next 10 to 20 years.

EFFECT OF PIPE PROCESSING ON STRESS CRACK RESISTANCE

The effect of pipe processing on SCR was evaluated using the SP-NCTL test. However, the evaluation was limited to Type S-annular pipes. Five different commercially available new pipes were evaluated, including Samples 1, 4, 5, 10, and 12. Samples 1 and 12 were made from the same resin but with diameters of 460 mm and 900 mm, respectively. Also, Samples 4 and 10 were made from the same resin but with diameters of 600 mm and 900 mm, respectively. Five SP-NCTL test specimens were taken directly from the pipe wall at two locations—the pipe crest and liner—as indicated in Figure 35. In the liner section, specimens were taken in both circumferential and longitudinal directions of the pipe. However, in Samples 5 and 12, no test specimens were taken from the crest location because of the unique profile of the crest section, as shown in Appendix C.

The SP-NCTL test was performed at an applied stress of either 2.62 or 4.14 MPa in order to achieve a failure time longer than 20 hr. The notch depth was modified because of the large variation in thickness at different locations on the pipe. The notch depth of each set of SP-NCTL test specimens was determined based on the stress intensity factor (K) that was calculated from tests performed on the corresponding plaque material. A detailed explanation regarding the stress intensity factor (K) is presented as Appendix H, which is not published herein. It was found that the notch depth was either 0.356 or 0.381 mm. In addition, the locations where test specimens were taken are also identified. The results of the study are presented in the following two sections.

Effect of Notch Position on the Failure Time of the SP-NCTL Test

The average failure times of SP-NCTL tests obtained from different pipe wall locations are given in Table 18. The data indicate that the failure time was very sensitive to the notch position with respect to the pipe surface at each pipe location. Regardless of diameter and resin type, specimens taken from the crest in the circumferential direction had a shorter failure

TABLE 17 Cell class based on ASTM D 3350 of 19 retrieved pipes

Site No.	Property						
	Density[1] (D1505) (g/cc)	MI[2] (D1238) (g/10 min.)	Flexural Modulus (D790) (MPa)	Yield Strength (D638) (MPa)	OIT[3] (D3895) (min.)	ESCR[4] (D1693)	SP-NCTL[5] (15%) (D5397) (hours)
M 294 spec.	**3** 0.941-0.955	**3** 0.4 to 0.15	**5** 758 to 1103	**4** 21 to 24	NA	**2** Cond. B	NA
Site A	0.9611	0.55	1259	44	20	failed	0.5
Site B+	0.9517	0.27	934	26	10.5	failed	4.7
Site D	0.9540	0.21	805	23	4.3	failed	13
Site E	0.9541	0.23	na	30	4.3	failed	5.0
Site F	0.9544	0.26	982	28	8.8	failed	9.4
Site G+	0.9573	0.36	983	39	11.1	failed	2.5
Site H	0.9483	0.14	927	26	18.0	passed	44
Site I	0.9533	0.26	1019	27	0.2	failed	8.6
Site J-1	0.9556	0.07	935	26	7.4	passed	313
Site J-2	0.9526	0.36	817	30	5.8	failed	2.9
Site K	0.9503	0.05	na	25	14.6	passed	38
Site L++	0.9494	0.04	648	27	10.3	passed	1800*
Site N++	0.9522	0.06	761	28	16.6	passed	212
Site O	0.9521	0.30	909	28	6.0	failed	4.7
Site P	0.9508	0.09	na	29	1.9	passed	14
Site R	0.9500	0.06	897	26	6.5	passed	273
Site U	0.9535	0.42	na	29	0.6	failed	6.3
Site V+	0.9539	0.05	na	27	17.2	passed	102
Site W+	0.9540	0.21	na	30	11.3	failed	6.3

carbon black content varies from 1% to 3%, except Site W contains 6.4%.

* data is extrapolated from higher stresses
\+ Field samples exhibited rapid crack propagation failure rather than slow crack growth
++ No cracking observed in field samples
na = non-available
NA = not applicable
[1] Calculated density resin values
[2] MI = melt index
[3] OIT = oxidative induction time
[4] ESCR = environmental stress crack resistance (criteria 24 hour/50% failure)
[5] SP-NCTL = single-point notched constant tensile load

time when the notch was introduced on the inner crest surface as opposed to the outer crest surface. Similar behavior was also observed for specimens taken from the liner location in the circumferential direction. However, for specimens taken from the liner along the longitudinal direction, the opposite behavior was detected; specimens with a notch on the outer liner surface failed earlier than those with a notch on the inner liner surface.

The difference in failure times between two notch positions could be caused by the following factors: orientation of polymer chains, induced bending stress, or residual stress, or both. The effect of orientation was studied by Lu et al., who found that the failure time of circumferential specimens was shorter than the longitudinal specimens in a polyethylene pressure pipe (*14*). In their study, however, only notching from the inner wall of the pipe was presented. If only considering notching from the inner wall, similar results were also obtained in pipe Samples 4 and 11. The failure time of circumferential liner specimens was shorter than the longitudinal liner specimens. This phenomenon was reversed, however, when the notch was introduced from the outer wall surface.

Induced bending stress also appeared to have a significant effect on specimens taken in the circumferential direction at both crest and liner locations. If stress in the pipe wall reached equilibrium after production, applying tensile stress onto the circumferential specimens induced tension on the inner wall surface and compression on the outer wall, as illustrated in Figure 36. When a notch was introduced on the inner wall, the actual tensile stress acting at the crack tip was higher than the applied stress, because of the induced bending stress. Alternatively, notching from the outer wall surface reduced the actual stress at the crack tip. Therefore, circumferential specimens with a notch on the inner wall had a shorter failure time than those notched on the outer wall.

The residual stresses in the liner may have caused a difference in failure times between two sets of specimens in the

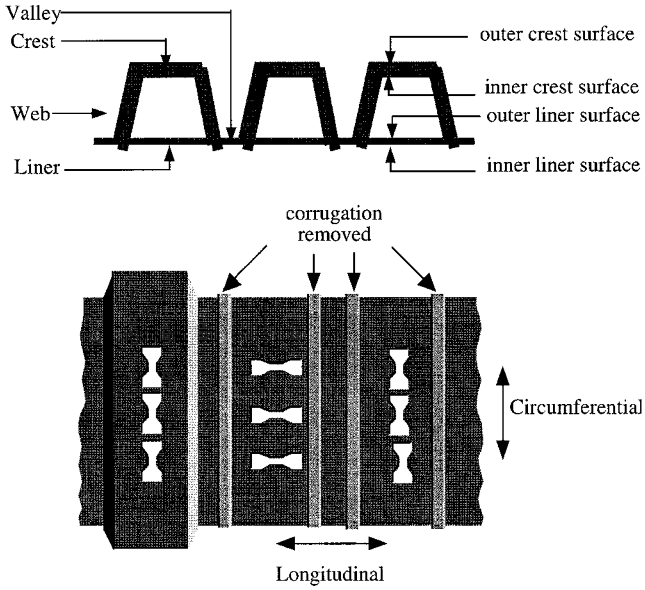

Figure 35. Locations at which SP-NCTL test specimens were taken from the pipe wall.

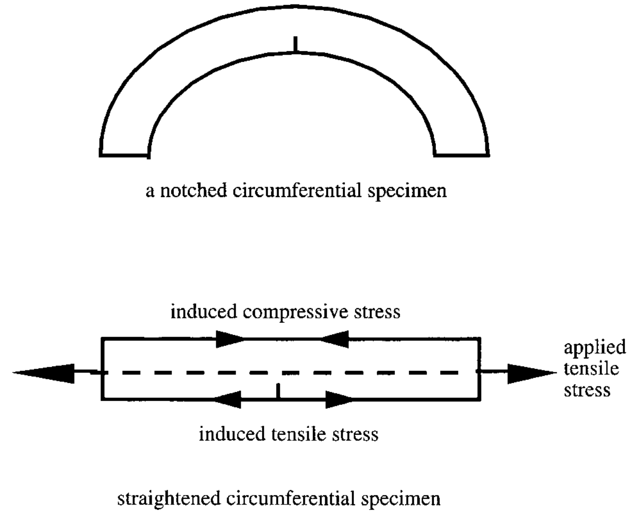

Figure 36. The induced stress on a straightened circumferential specimen.

longitudinal direction. A qualitative test was used to confirm the existence of residual stress in the liner. A small rectangular specimen, 50 mm long and 20 mm wide, was taken from the liner portion of the pipe. Initially, there was no bending in the specimen, which was placed on top of a hot plate at a temperature of approximately 80°C. After a while, contraction occurred on the inner liner surface, causing the specimen to bend. This indicated that there was a compressive stress present in the inner liner surface and a tensile stress in the outer liner surface. Thus, when the notch was introduced on the inner wall, the residual compressive stress retarded the crack growth, resulting in a long failure time. An opposite effect resulted when the notch was introduced on the outer wall.

In all five tested pipes, the shortest failure time resulted from specimens taken in the longitudinal direction and notched from the outer liner surface, that is, the notch was in the circumferential direction. The notch grew from the outer surface through the thickness of the liner. Such cracking was similar to that which had occurred in the field, suggesting that the residual stress along the longitudinal direction of the pipes could be one of the contributing factors leading to circumferential cracking in pipes.

Comparing Failure Times of SP-NCTL Tests Between Plaques and Pipe Walls

As indicated in the previous section, at the same pipe wall location, different notch positions resulted in different failure times. The shortest failure time was used to compare data obtained from the compression plaque and that obtained from pipe wall material. Table 19 shows the failure time ratio

TABLE 18 SP-NCTL test results of five evaluated pipe samples

Specimen Locations (direction)	Notch Location (orientation)	Average Failure Time in hours (Standard Deviation)				
		Sample #1 at 4.14 MPa	Sample #12 at 4.14 MPa	Sample #5 at 4.14 MPa	Sample #4 at 2.62 MPa	Sample #11 at 2.62 MPa
Crest (circumferential)	inner crest surface (longitudinal)	36 (± 4)	-	-	20 (± 3)	47 (± 7)
	outer crest surface (longitudinal)	62 (± 18)	-	-	362 (± 127)	109 (± 39)
Liner (circumferential)	inner liner surface (longitudinal)	47 (± 4)	64 (± 11)	22 (± 3)	20 (± 1)	25 (± 3)
	outer liner surface (longitudinal)	73 (± 3)	80 (± 8)	32 (± 3)	90 (± 26)	> 400
Liner (longitudinal)	inner liner surface (circumferential)	112 (± 11)	> 200	> 200	> 450	> 400
	outer liner surface (circumferential)	59 (± 2)	52 (± 1)	18 (± 2)	14 (± 2)	14 (± 2)

TABLE 19 Failure time ratio between molded plaque and different locations of pipe wall

Specimen Locations (direction)	Notch Location (orientation)	Failure Time Ratio				
		Sample #1 at 4.14 MPa	Sample #12 at 4.14 MPa	Sample #5 at 4.14 MPa	Sample #4 at 2.62 MPa	Sample #11 at 2.62 MPa
Crest (circumferential)	inner crest surface (longitudinal)	1.7	-	-	1.6	0.7
Liner (circumferential)	inner liner surface (longitudinal)	1.4	1	1.9	1.6	1.2
Liner (longitudinal)	outer liner surface (circumferential)	1.1	1.2	2.3	2.2	2.2

of compression plaque to various pipe locations at the same applied stress, that is, 2.62 and 4.14 MPa. In general, the compression plaque had a longer failure time than the corresponding pipe wall materials, except for the crest location in Sample 11. The ratio varied from pipe to pipe because of differences in bending and residual stresses induced during the manufacturing process as explained previously.

Of the various pipe wall locations, the liner in the longitudinal direction was the most important one because this was the location where the field circumferential cracking took place. A ratio of 2.2 was found in Samples 4, 5, and 11, and a ratio of 1.2 was found in Samples 1 and 12. This difference may have been due to the residual stress. Samples 4, 5, and 11 may have had a higher residual stress than Samples 1 and 12. For specimens taken from the liner in the circumferential direction, a range of ratio values, from 1.0 to 1.9, was found. The variation did not seem to correlate either to the pipe diameter or to the manufacturing process. At the crest location, Samples 1 and 4 exhibited a similar ratio value. In contrast, Sample 11, which was a large diameter pipe, showed a much lower value. The bending stress in the two smaller diameter pipes may have enhanced the crack propagation.

The effect of pipe processing on the SCR of the resin was clearly demonstrated. However, the current research covers only Type S-annular pipes with diameters of 460, 600, and 900 mm. Other pipe profiles, including helical and honeycomb, have not been studied. The complex corrugation profile of these two types of pipe makes the SP-NCTL test difficult to perform, because the existence of voids in the wall thickness prohibits the continuation of crack growth. An alternative test method, such as the constant tensile load (CTL) test, would be more appropriate to assess the SCR of finished pipe products. (The description of the CTL test is presented in Chapter 4.)

CORRELATION BETWEEN SCR AND MATERIAL PROPERTIES

It is generally known, as explained by Gabriel et al. (*1*), that SCR could be related to basic polymer properties, such as density and MI. In this section of the report, the possible relationship between these two properties and SCR was investigated. The failure time of the SP-NCTL test at 15% yield stress was used to represent the SCR of the pipe material. Both commercially available new pipes and retrieved pipes were included. Two graphs were developed: failure time versus density and failure time versus MI, as shown in Figures 37 and 38, respectively. A general trend was observed in the data points of both graphs. As expected, failure time increased as density and MI decreased. The decrease in density implied an increase in the amorphous phase in the polymer, whereas the decrease in MI generally signified an increase in molecular

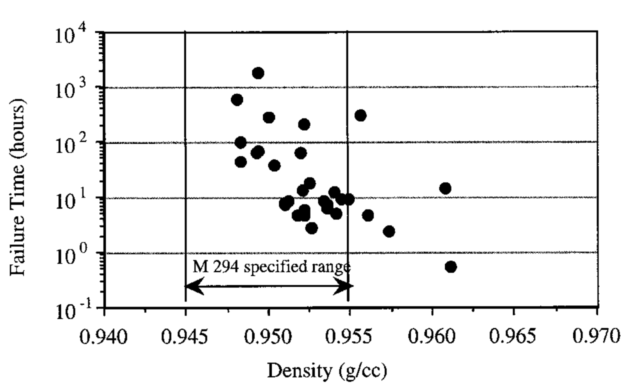

Figure 37. Failure time versus density plotted for all evaluated pipe samples.

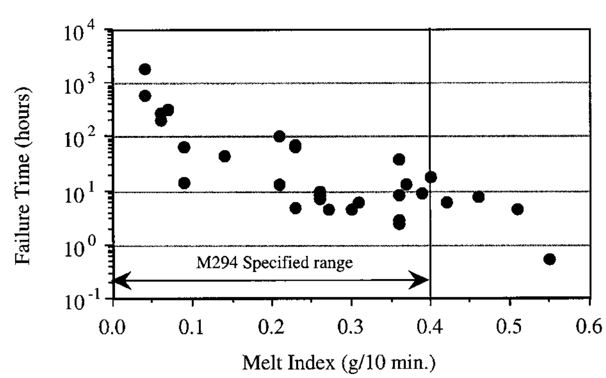

Figure 38. Failure time versus melt index plotted for all evaluated pipe samples.

weight of the polymer. Both of these changes could have improved the SCR of the polymer.

It is observed that within the specified range of M 294, the failure time varied by 1,000 times. For example, in materials having a density value of approximately 0.952 g/cm^3, the range of failure time varied from 8 to 200 hr. Similar behavior was also seen in the MI graph. The analysis illustrated that SCR was a unique characteristic of the polymer that could be influenced not only by the basic polymer properties, but also by other factors, such as the polymerization process, the types of co-monomer present, and so forth. To ensure the resin has an adequate SCR, the resin must be evaluated by a test that is designed to challenge this specific property.

CHAPTER 3

INTERPRETATION, APPRAISAL, APPLICATIONS

The objectives of this project were to explore and, if appropriate, to validate the SP-NCTL test as a qualitative predictor of slow crack-growth resistance in HDPE corrugated pipes and to determine a minimum failure time requirement by correlating the test with field performance of the pipe. The interpretation, appraisal, and applications of the study are presented below:

FIELD EXPERIENCES—QUESTIONNAIRES AND FIELD INVESTIGATIONS

The responses to Questionnaire Nos. 1 and 2 and the site visits to collect samples provided considerable insight into the past performance of corrugated HDPE pipes. A significant number of corrugated HDPE pipes with cracks were located through the questionnaires and field investigations. Much of the cracking was associated with installation problems that led to deflection or longitudinal bending. There were sufficient cases of cracking under moderate deflection levels, however, to warrant attention to the material quality and product design, as well as to the installation procedure and detailing of pipe junctions with rigid structures such as headwalls. Construction recommendations, which are often applicable to other types of pipe, include the following:

- Control of backfill material and construction procedures is extremely important to control deflections. The level of construction control that can be imposed is an economic decision for an owner. The simplest procedure that should be required for any flexible pipe installation is a deflection check at the completion of construction. Monitoring the actual construction is also desirable, including checks on the gradation of backfill material, haunching procedures, and backfill densities. These checks should be imposed on projects where the consequences of failure are significant. Pipe structural backfill under roadways or under deep fills should only be coarse grained soils (A-1, A-2-4, A-2-5, or A-3 per AASHTO M 145). An alternative to full-time inspection during backfilling is random re-excavation of test pits after backfilling has progressed to the top of the pipe.
- Pipe terminations should be detailed to prevent erosion. Sites that might be susceptible to erosive conditions at outlets should have cut-off walls or other treatments to ensure good performance.
- Criteria for longitudinal bending should be established. The material testing indicates that circumferential cracking may result in part from residual stresses; however, the problem should also be addressed in the field. Inspection personnel will benefit from more definitive guidance on allowable longitudinal deviations. It may be appropriate to establish a test for longitudinal strength of the pipe. The test would need to address the viscoelastic nature of the plastic material and its sensitivity to slow crack growth.

Many cracked field pipes deflected beyond the generally accepted deflection limit of 7.5% for thermoplastic culvert pipe or had other installation problems causing high strains. However, the 7.5% limit on deflection is a service allowable state, and the occurrence of cracking should be considered an ultimate state. Cracking should not occur until deflection levels are well beyond the allowable state; however, no criteria for ultimate deflection levels for thermoplastic pipe have been established. Historically, the deflection limit for metal pipe was set at 5%, based on the philosophy that structural failure would occur at a deflection level of 20% and a safety factor of 4 was appropriate. If this criterion were to be applied to thermoplastic pipe (the researchers are not proposing this), then all but two of the field-investigated installations would be expected to provide good service without cracks developing. Even with an ultimate deflection level set at 12% to 15%, many of the field pipes would still be expected to survive without cracking, especially because these pipes were investigated at service lives of 1 to 16 years, whereas the design life is expected to be 50 years. Finally, when computing allowable deflection levels for pipe installations, many standards for thermoplastic pipe allow the “tolerance packages” to account for out of roundness prior to installation and for deviations from tolerance on product dimensions. The tolerance packages can increase the allowable deflection by several percentage points, for example, a pipe deflected 10% may often be considered acceptable when the allowable deflection is adjusted for the tolerance package, even though the “allowable” deflection is 7.5%. While AASHTO has not set standards for ultimate deflection levels or tolerance packages at this time, it is certain that pipe should be expected to deflect well over 10% without reaching any ultimate limit state. The pipe at investigated sites covers the range where an ultimate deflection level is likely to be set.

VALIDITY OF THE SP-NCTL TEST

The test condition of the SP-NCTL test was determined based on the results of P-NCTL tests. Fourteen commercially available new pipe samples and 19 retrieved samples were evaluated by the P-NCTL test. After considerable testing, a yield stress value of 15% was selected as the appropriate applied stress for the SP-NCTL test. This was because the linear relationship between applied stress and failure time ceased to exist at 10% yield stress. In addition, a shorter failure time could be achieved for QC purposes. The coefficient of variation (i.e., standard deviation divided by the mean value) for the failure time at 15% yield stress ranged from 4% to 18%. Ninety-four percent of the 33 tested materials had a coefficient of variation less than 15%; thus, a value of 15% was used as the minimum value in the recommendations. It should be noted that this coefficient of variation value is based on performance in a single laboratory. This value may be higher among other laboratories. An interlaboratory program on the complete test procedure (including plaque making and SP-NCTL testing) is needed to verify this value with more confidence.

The SP-NCTL test results—failure times at 15% yield stress—of the 29 tested pipe samples are shown in Figure 39. (Note that data obtained from Sites B, G, V, and W field samples were excluded in this analysis because their cracking was not caused by the slow crack-growth mechanism.) The data were further divided according to the corrugation profile type. Data from S-helical, C-helical, annular, and honeycomb pipes were arbitrarily shifted to 15.1, 15.05, 15, and 14.95 of the yield stress, respectively. The results indicated that the SP-NCTL test effectively distinguished the SCR of different HDPE resins. The overall failure time ranged from 0.5 hr to 1,000 hr. The failure time range varied for each pipe profile. Types C- and S-helical pipes had the widest ranges, and the Type S-honeycomb pipes had the narrowest range.

In addition, data seemed to indicate a correlation between the SP-NCTL test and ESCR test. Materials with a SP-NCTL failure time of less than 14 hr failed the current ESCR test criteria. Such a correlation could serve as a guideline for resin and pipe manufacturers in understanding the performance of their resins in the SP-NCTL test.

MINIMUM FAILURE TIME RECOMMENDATION OF THE SP-NCTL TEST FOR HDPE CORRUGATED PIPE RESINS

The recommended minimum failure time for the SP-NCTL test was primarily based on results presented in Figure 39, but other external factors were also considered. These external factors included pipe profile design, deflection and buckling of the pipe, and longitudinal bending of the pipe.

The Type S-helical pipes had the greatest variation in failure times, from 10 to 580 hr. The maximum failure time of the retrieved cracked pipe was approximately 300 hr. For retrieved cracked Type C-helical pipes, a failure time of less than 10 hr was measured. In contrast, a failure time greater than 100 hr was measured on pipes retrieved from Sites L and N. These two pipes were reported to have no cracking but were associated with a large deflection. In particular, the pipe in Site L exhibited a 16% vertical deflection. This suggests that SCR of the resin is a critical parameter to reduce the cracking potential of HDPE pipe in the field. Although some of the helical pipes were manufactured from resins with a high SCR, these pipes are more susceptible to cracking in the field because of their complex corrugation profile. According to the pipe manufacturers, the production of Type C- and S-helical pipes in culvert size has been terminated. Thus, consideration of the minimum failure time for current HDPE corrugated

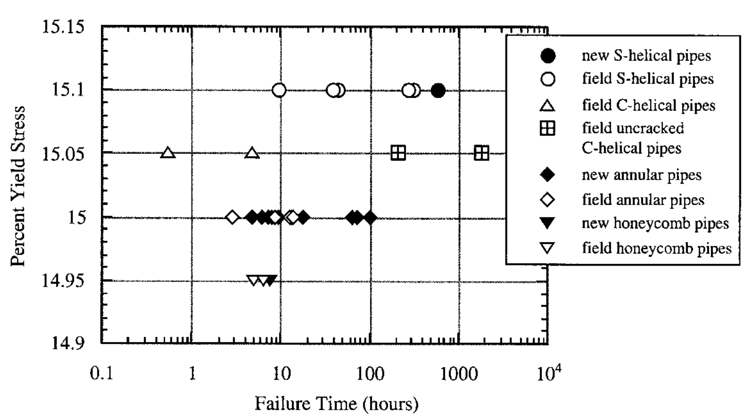

Figure 39. Failure times of commercially available new pipes and retrieved pipes separated according to their corrugation profile.

pipes excluded this group of data and was limited to Type S- and C-annular pipes and Type S-honeycomb pipe.

However, a minimum failure time is still recommended for Type C- and S-helical pipes to provide a baseline requirement for any future production from outside the United States. The pipes in Sites L and N were used as reference points. A minimum failure time of 400 hr is recommended for these two types of pipes. This value is between those of Sites L and N and is also above the highest failure time measured from the cracked pipe.

For Type S-annular, Type C-annular, and Type S-honeycomb pipes, there was a significant amount of overlapping in failure times obtained from commercially available new pipes and retrieved pipes. This suggests that the SCR of these resins were similar, even though some of the pipes had been exposed to site ambient environments for 7 years. The failure time of annular pipes varied from 3 to 100 hr, whereas the failure time of the honeycomb pipes was between 5 and 8 hr. The Type S-honeycomb pipe at Site U had a large vertical deflection (reaching 20%) as well as buckling. Such behavior of the pipe was likely associated with poor installation, which subsequently led to cracking in the pipe. The failure time of this pipe was not included in the determination of the minimum failure time.

For the remaining four cracked pipes, the maximum vertical deflections ranged from 3% to 11%. These values may not be unusual in the field, especially for localized deformations. The longest failure time of these four cracked pipes was 14 hr, which corresponds to Site P. The pipe at Site P exhibited a 5% vertical deflection without buckling or bending. This suggests that cracking was most likely induced by the material rather than the installation. Thus, the lowest limit for resins can be established at 14 hr. To ensure 95.4 % (i.e., mean value plus two standard deviations) of the material exceeded 14 hr, an average failure time of 24 hr was required based on a 15% coefficient of variation, as illustrated in the following calculation:

mean value = 24 hr
standard deviation (σ) = 24 hr $*$ 15% = 3.6 hr,
$2\sigma = 2 * 3.6$ hr = 7.2 hr
minimum value = mean value $- 2\sigma$ = 24 hr $-$ 7.2 hr = 16.8 hr

It should be recognized that the pipe at Site P was manufactured from a resin that passed the ESCR test. Resins used in the other three cracked samples failed the current ESCR test. This suggests that the recommended failure time should result in resins with SCR better than the current SCR requirement.

The recommended specification for the SP-NCTL test of HDPE corrugated pipes includes the following:

1. Resins for Type S- and Type C-annular Pipes and Type S-honeycomb Pipes
   - Compression molded plaques are prepared according to ASTM D 1928, Procedure C. The thickness of the plaques shall be 1.78 mm ± 0.05 mm.
   - Applied stress shall be at 15% yield stress of the molded plaque.
   - Five test specimens should be used.
   - The average failure time must exceed 24 hr.
   - None of the five test specimens should fail in less than 17 hr.

     (Because the coefficient of variation of the test is ±15%, the standard deviation (σ) of the test with an average failure time of 24 hr will be equal to 24 $*$ 0.15 = 3.6 hr. ASTM uses two standard deviations to define the variability of the test. Thus, the upper and lower limits are 24 ± 7 = 17 and 31 hr, respectively.)
2. Resins for Type S- and Type C-helical Pipes
   - Compression molded plaques are prepared according to ASTM D 1928, Procedure C. The thickness of the plaques shall be 1.78 mm ± 0.05 mm.
   - Applied stress shall be at 15% yield stress of the molded plaque.
   - Five test specimens should be used.
   - The average failure time must exceed 400 hr.
   - None of the five test specimens should fail in less than 280 hr.

     (Because the coefficient variation of the test is ±15%, the standard deviation (σ) of the test with average failure time of 400 hr will be equal to 400 $*$ 0.15 = 60 hr. ASTM uses two standard deviations to define the variability of the test. Thus, the upper and lower limits are 400 $*$ 120 = 280 and 520 hr, respectively.)

Figure 40 is a re-plot of Figure 39, incorporating the minimum average failure time limit for these two groups of materials.

MINIMUM FAILURE TIME RECOMMENDATION OF THE SP-NCTL TEST FOR HDPE CORRUGATED PIPES

The SCR study of the final pipe products was only performed on Type S-annular pipes. The other profiles, helical and honeycomb pipes, were not evaluated because of the complex corrugation profile that limited the performance of the SP-NCTL test.

On the basis of the test data obtained from the Type S-annular pipes, it is clear that the pipe process has a strong impact on the SCR of the resin. The finished pipes generally showed a lower SCR than the corresponding pipe resin. However, the reduction factor varied greatly from 0.7 to 2.3 depending on the size and process of the pipe. Both residual and bending stresses had a large influence in the performance of the SP-NCTL test.

At the present time, it seems premature to recommend the SP-NCTL test as the SCR test for finished corrugated pipes.

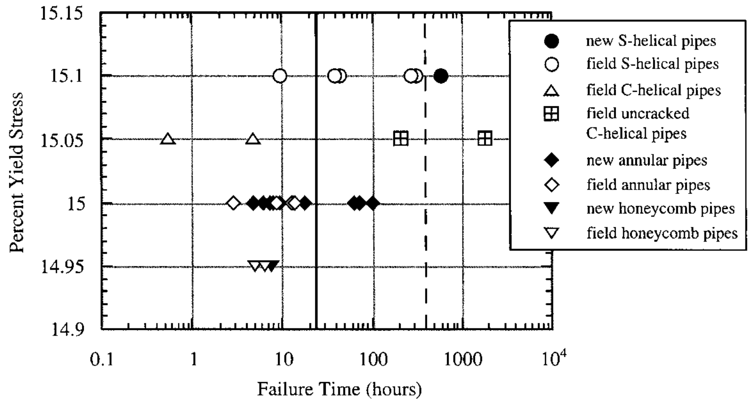

Figure 40. Failure times of commercially available new pipes and retrieved pipes along with the minimum failure time limits. (The solid line is the limit for annular and honeycomb pipes; the dotted line is the limit for helical pipes.)

SPECIFICATIONS

The following three AASHTO specifications are being modified based on the finding of this research:

- AASHTO Standard Specification for Corrugated Polyethylene Pipe: M 294,
- AASHTO Standard Specification for Highway Bridges (Section 18), and
- AASHTO LRFD Bridge Design Specifications.

The item to item change in each of these specifications is included in Appendix I. Basically, there are two issues involved in the modification.

Note that there is no proposed change to the M 252 Specification, because all evaluated pipes in this study had diameters greater than 300 mm. The implementation of test results on small diameter pipes is not certain.

Incorporating the SP-NCTL Test into the Specification

The test procedure of the SP-NCTL test and specific minimum failure times have been inserted into M 294 Specification for basic resin requirements, and the recommendation has been further divided according to the pipe profile. It should be emphasized that all evaluated pipes in this study had diameters greater than 300 mm. Testing of smaller diameter pipes has not been validated. Thus, adapting these recommendations in Specification M 252 for pipes with diameters less than 300 mm should be approached cautiously.

For finished pipe products, there is no recommendation regarding the SP-NCTL test. However, modifications are proposed to make the 90° ESCR pipe test a stand-alone test.

For the other two specifications, Section 18 and LRFD Bridge Design, material requirements are referred to the M 294 Specification.

Cell Classification Modification

The cell classification should be modified in these three specifications to reflect changes in the SCR tests. The current cell class number for the ESCR is “2.” This number should be changed to “0” if the SP-NCTL test is adopted. The specification should not require two different SCR tests. The cell class “0” in ASTM D 3350 is referred to “unspecified.” Instructions for the SP-NCTL test procedure and requirements should then be incorporated into the appropriate section(s) of the specification to guide the user.

CHAPTER **4**

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The conclusions of the study are presented in two parts: field investigations and laboratory studies.

Field Investigations

As described in the Findings section of the report and documented in Appendix B, the majority of the responses expressed a good or satisfactory experience on the overall performance of the HDPE corrugated pipes, even though the mailing distribution was targeted in part to locate sites with cracking. Of the 62 sites that had problems associated with deflection, buckling, and cracking, 29 sites were identified and visited. Following are the conclusions related to cracking that are drawn from the field investigation:

- Circumferential cracks were the dominant type of cracking, signifying the existence of longitudinal stresses in the pipe. The stresses could have been caused by the combination of localized deformation, longitudinal bending, excessive deflection and buckling, and residual stress in the pipe.
- For Type S-helical and annular pipes, the circumferential cracking took place at the junction between the corrugation and the liner where the stress concentration was the highest. Cracks typically initiated from the outer surface and grew through the liner thickness. Thus, pipe geometry is one of the factors that influence the SCR of the pipe. This type of cracking may not lead to collapse of the pipe but could affect the hydraulic performance.
- Longitudinal cracking was also observed in four of the sites. Some of the longitudinal cracks propagated through the outer corrugation, allowing soil to infiltrate into the pipe. This type of cracking could have a critical effect on the long-term soil/pipe interaction and should be avoided completely.
- Poor installation was found to be the likely cause for excessive deflection and buckling in some of the sites. Appropriate construction procedures are essential in achieving proper installation.

Laboratory Studies

Fourteen commercially available new pipe samples and 19 retrieved samples were evaluated for their SCR as well as their basic material properties. Following are the conclusions drawn from the laboratory studies:

- The majority of the tested pipe samples conformed to the current ASTM D 3350 Specification for density, MI, flexural modulus, and tensile yield strength. The carbon black content varied significantly between the samples; many pipe samples had values below the lower specified limit. For the ESCR test, 8 out of the 14 commercially available new pipes and 11 out of the 19 retrieved samples failed the required criterion. This indicates that the SCR of pipe materials must be properly evaluated.
- The pipe resins were also assessed using the P-NCTL test for their SCR property. Based on the test results, a 15% yield stress was selected as the applied stress for the SP-NCTL test.
- The SP-NCTL test data of the 33 pipe samples—failure time at 15% yield stress—ranged from 0.5 to 1,800 hr, reflecting a large variation in their SCR behavior. However, pipes made from high SCR resin, for example, Site L, showed a greater tolerance to cracking even under a large deflection. This demonstrates that SCR is an important parameter to prevent cracking in the field.
- Based on SP-NCTL test data obtained from 19 retrieved samples, a minimum failure time was determined for two different groups of corrugated pipes:
  Group 1—Type C- and S-helical pipes. It is recommended that the minimum average failure time be greater than 400 hr.
  Group 2—Type C-annular, Type S-annular, and Type S-honeycomb pipes. It is recommended that the minimum average failure time be greater than 24 hr.
- Regarding the SCR of final pipe products, the bending and residual stresses that were induced by the manufacturing process of Type S-annular pipe were shown to have a large effect on the SCR of the resin. The residual stress had the greatest effect on the longitudinal direction of the liner with crack growth from the outer surface

through the liner thickness. This implies that residual stress could be one of the factors that led to pipe cracking in the field.
- For other pipe profiles, helical and honeycomb, the SP-NCTL test was not performed on their finished products because of complex corrugation and void existence.
- At present, the SP-NCTL test is not recommended for use in the evaluation of the SCR of finished pipe products.

SUGGESTED RESEARCH

There are three areas that require additional research to further the understanding of the long-term performance of corrugated pipes.

Constant Tensile Load Test on Finished Pipe Products

The limitation of the SP-NCTL test on the finished corrugated pipes was identified in this study. An alternative test that can evaluate the SCR of all types of corrugated pipes is urgently needed, because the current 90° ESCR pipe test is impractical for large diameter pipes. In addition, the test does not test the pipe location that is sensitive to stress cracking.

In this study, a new SCR test was explored. The new test is called the constant tensile load (CTL) test, which is designed to assess the SCR of the finished pipe at any location. The initial tests were performed on the liner-corrugation junction of both Type S-helical and Type S-annular pipes. This is because the most common location for cracking in Type S pipes was at the junction between the liner and the corrugation, as illustrated in Figure 2 in the report. The crack initiated from the outer liner surface and grew through the thickness of the liner. This cracking behavior implies that the junction is the location most susceptible to cracking and should be evaluated accordingly.

Test specimens were taken directly across the junction region of the pipe, as illustrated in Figure 41. The specimen size used in the CTL test was in accordance with ASTM D 638, instead of ASTM D 5397, because the constant width section of the D 638 tensile specimen accommodated the entire interfacial junction, as revealed in Figure 42. The most important difference between the CTL test and the SP-NCTL test is that no notch was introduced to the CTL test specimens. The test specimens were subjected to a single applied stress corresponding to a 15% yield stress of the molded plaque. The test conditions were the same as the NCTL test, that is, in 10% Igepal solution at 50°C. The failure occurred at one of the junctions where the stress was concentrated. The failure time of the CTL specimen depends on factors such as the resin, internal defects, and the junction

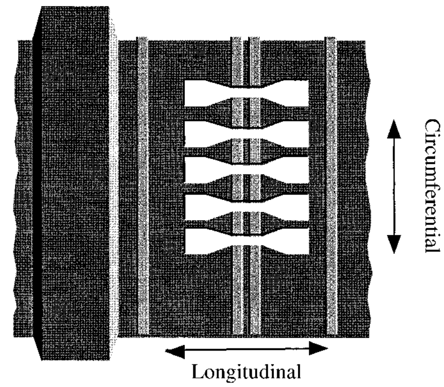

Figure 41. Location of the CTL test specimens across the junction.

geometry. Thus, the sensitivity of the pipe profile with respect to SCR can be evaluated.

Evaluation of Antioxidants

The large variation in OIT test data indicated that there were different antioxidant packages being used in the tested HDPE corrugated pipes. Because the function of antioxidants is to preserve the property of the polymer, a minimum required amount for the commonly used antioxidant package should be determined to ensure a desired design lifetime. A laboratory acceleration test together with the Arrhenius equation

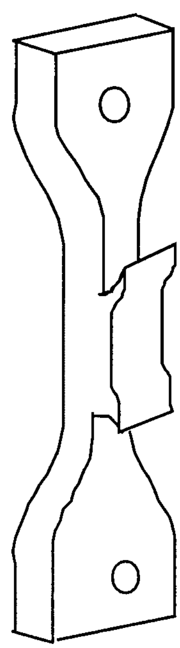

Figure 42. Sideview of the CTL test specimen, using ASTM D 638 Type IV dimensions.

can be used to predict the lifetime of the antioxidant package and the polymer (*9*, *12*).

Impact Test

Cracking in four retrieved samples was found to be via a rapid crack propagation rather than a slow crack growth. As described in the findings of the report, rapid crack propagation is associated with cool temperature and dynamic loading. The current required drop weight test should be properly evaluated, because this test may not be applicable for large diameter pipes. A study performed on gas pipes has found that large diameter pipes are more susceptible to rapid crack propagation (*13*).

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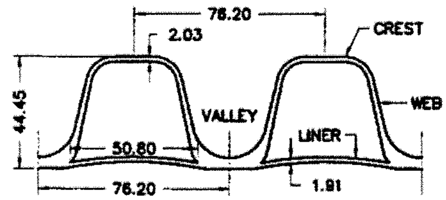
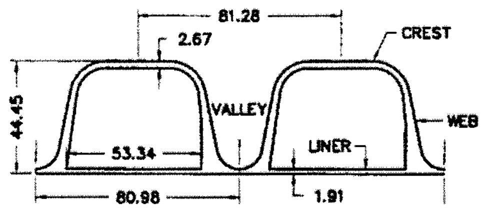
APPENDIX C

CORRUGATION PROFILES OF FOURTEEN COMMERCIALLY AVAILABLE NEW PIPES

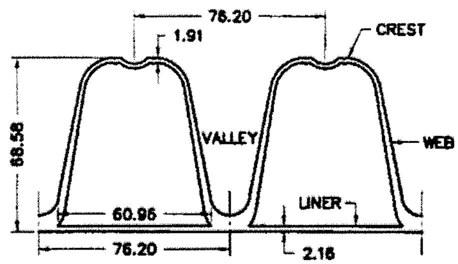
Figure 1 shows the corrugation profiles of 14 commercially available new pipes.



Pipe Sample #1, 2, & 3
(18"ø ANNULAR)

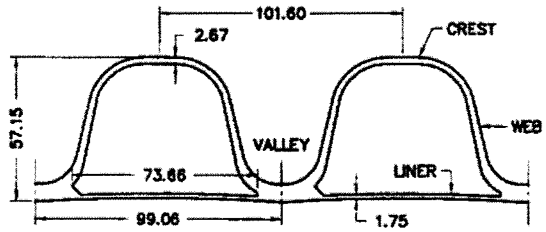


Pipe Sample #4
(24"ø ANNULAR)

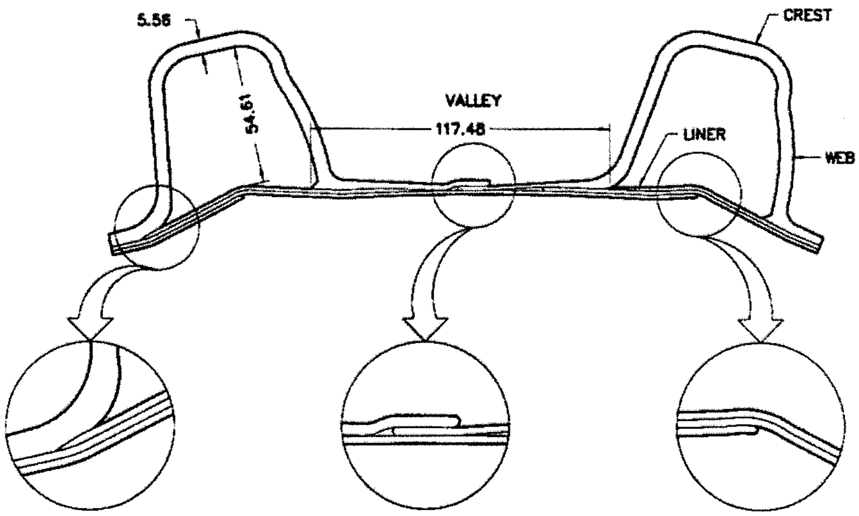


Pipe Sample #5 & 6
(24"ø ANNULAR)

Figure 1. Cross-sectional profiles of various pipes with approximate dimensions in millimeters.



Pipe Sample #7
(24"ø ANNULAR)



Pipe Sample #8
(24"ø HELICAL)

Figure 1. Continued.

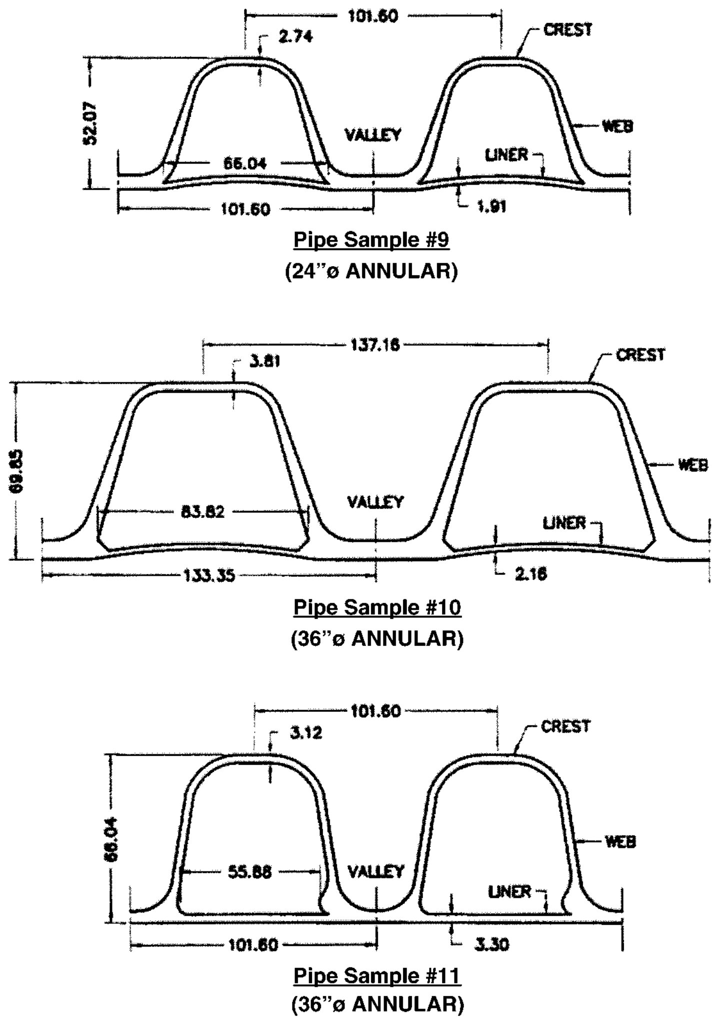
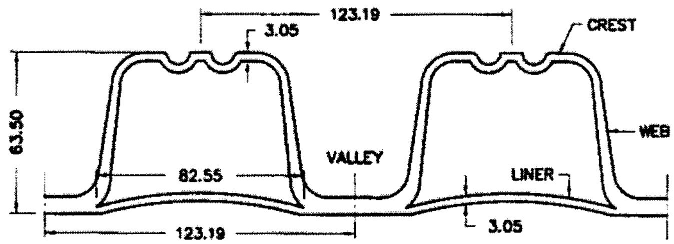
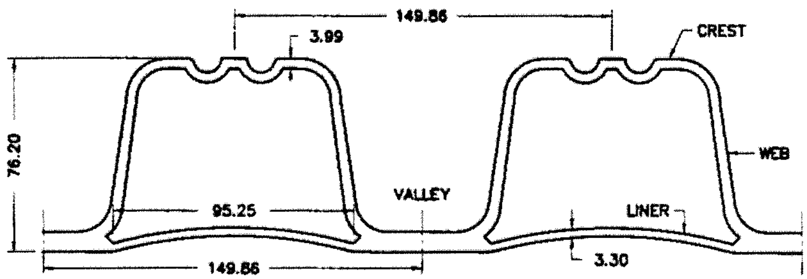


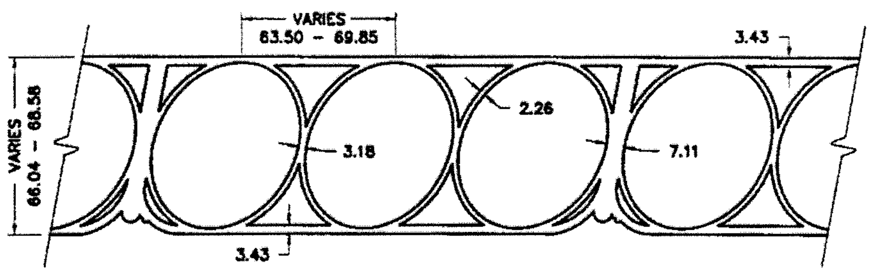
Figure 1. Continued.



Pipe Sample #12
(36"ø ANNULAR)



Pipe Sample #13
(48"ø ANNULAR)



Pipe Sample #14
(48"ø HONEYCOMB)

Figure 1. Continued.

APPENDIX I

MODIFICATIONS TO AASHTO SPECIFICATIONS

Appendix I contains the recommended modifications to the following AASHTO specifications:

I-1. AASHTO Standard Specification for Corrugated Polyethylene Pipe: M 294;
I-2. AASHTO Standard Specification for Highway Bridges (Section 18—Soil-Thermoplastic Pipe Interaction Systems); and
I-3. AASHTO LRFD Bridge Design Specifications.

The modified language is underlined.

I-1. MODIFICATIONS TO AASHTO STANDARD SPECIFICATION FOR CORRUGATED POLYETHYLENE PIPE, 300 mm to 900 mm: M 294

Item 1–Insert ASTM D5397 in Section 2 (inserted section is underlined)

Current specification	*Modified specification*
2. REFERENCED DOCUMENTS	2. REFERENCED DOCUMENTS
2.1 *ASTM Standards*:	2.1 *ASTM Standards*:
D 3350 Standard Specification for Polyethylene Plastics Pipe and Fittings Materials	D 3350 Standard Specification for Polyethylene Plastics Pipe and Fittings Materials
	D 5397 Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test.
F 412 Terms Relating to Plastic Piping Systems	F 412 Terms Relating to Plastic Piping Systems

Item 2–Modifications to Cell Class and Insertion of the SP-NCTL Test into Section 6 (changes are underlined)

Current specification

6.0 MATERIALS

6.1. Basic Materials

6.1.1 *Extruded Pipe and Blow Molded Fittings*: Pipe and fittings shall be made of virgin PE compounds which conform with the requirements of cell class 335420C as defined and described in ASTM D 3350, except that the carbon black content shall not exceed 5 percent, and the density shall not be less than 0.945 g/cm^3 nor greater than 0.955 g/cm^3. Compounds that have higher cell classifications in one or more properties, with the exception of density, are acceptable provided product requirements are met.

6.2 *Reworked Materials*: In lieu of PE, clean reworked material may be used by the manufacturer, provided that it meets the cell class requirements as described in Section 6.1.

Modified specification

6.0 MATERIALS

6.1 Basic Materials

6.1.1 *Extruded Pipe and Blow Molded Fittings*: Pipe and fittings shall be made of virgin PE compounds which conform with the requirements of cell class <u>335400C</u> as defined and described in ASTM D 3350, except that the carbon black content shall not exceed 5 percent, and the density shall not be less than 0.945 g/cm^3 nor greater than 0.955 g/cm^3. Compounds that have higher cell classifications in one or more properties, with the exception of density, are acceptable provided product requirements are met. <u>For environmental stress crack resistance, compounds shall be evaluated using the single point notched constant tensile load (SP-NCTL) test, according to the procedure described in Section 9.5 of the Specification.</u>

6.2 *Reworked Materials*: In lieu of PE, clean reworked material may be used by the manufacturer, provided that it meets the cell class requirements, <u>and the minimum failure time of the SP-NCTL test</u> as described in Section 6.1.

Item 3–Modifications to Section 7.6 (changes are underlined)

Current specification

7.6 *Environmental Stress Cracking*–There shall be no cracking of the pipe when tested in accordance with Section 9.4.

Modified specification

7.6 *Environmental Stress Cracking*:

7.6.1 For finished pipe, there shall be no cracking of the pipe when tested in accordance with Section 9.4.

7.6.2 Resin compounds shall be tested in accordance with Section 9.5. For helical Type C, S, CP, and SP pipes, the average failure time must exceed 400 hours. None of the five specimens shall have failure times less than 280 hours. For annular Type C, S, CP and SP pipes and honeycomb Type D pipes, the average failure time must exceed 24 hours. None of the five test specimens shall have failure times less than 17 hours.

Item 4–Modifications to Section 9 (changes are underlined)

Current specification

9.4 *Environmental Stress Cracking*–Test sections of the tubing for environmental stress cracking in accordance with ASTM D1693, except for the following modification:

9.5 *Fittings:*

9.6 *Dimensions:*

Modified specification

9.4 *Environmental Stress Cracking of Finished Pipe* –Test sections of the pipe for environmental stress cracking in accordance with ASTM D1693, except for the following modification:

9.5 Environmental Stress Cracking on Basic Resin–Test basic resin compounds for environmental stress cracking in accordance with the ASTM D5397-Appendix, the SP-NCTL test, except for the following modifications:

9.5.1 Resin compounds shall be compression molded according ASTM D 1928, Procedure C. The thickness of the plaque shall be 1.8 mm ± 0.5 mm (0.071 in. ± 0.002 in).

9.5.2 Five test specimens shall be taken from the molded plaque along the same orientation.

9.5.3 Applied stress of the test shall be 15% of the yield strength of the compound according to ASTM D 638 Type IV.

(Note the change to the subsequent section numbers.)

9.6 *Fittings:*

9.7 *Dimensions*:

I-2. MODIFICATIONS TO AASHTO STANDARD SPECIFICATION FOR HIGHWAY BRIDGES (SECTION 18—SOIL-THERMOPLASTIC PIPE INTERACTION SYSTEMS)

Item 1–Modifications to Section 18.4.3.1.2 (changes are underlined)

Current specification

18.4.3.1.2 Corrugated PE pipe requirements–

AASHTO M 294

Mechanical Properties for design

Initial		50 Year	
Min. Tensile Strength (MPa)	Max. Mod. of Elast. (MPa)	Min. Tensile Strength (MPa)	Max. Mod. of Elast. (MPa)
21	758	6.3	152

Minimum cell class, ASTM D 3350, 335420C

Allowable long term strain = 5%

Modified specification

18.4.3.1.2 Corrugated PE pipe requirements–

AASHTO M 294

Mechanical Properties for design

Initial		50 Year	
Min. Tensile Strength (MPa)	Max. Mod. of Elast. (MPa)	Min. Tensile Strength (MPa)	Max. Mod. of Elast. (MPa)
21	758	6.3	152

Minimum cell class, ASTM D 3350, 335400C, with additional environmental stress crack resistance evaluation according to SP-NCTL test as set forth in AASHTO M 294.

Allowable long term strain = 5%

I-3. MODIFICATIONS TO AASHTO LRFD BRIDGE DESIGN SPECIFICATIONS

Item 1–Modifications to Table 12.12.3.3-1 (changes are underlined)

Current specification	*Modified specification*
Table 12.12.3.3-1 *Mechanical Properties of Thermoplastic Pipes*	Table 12.12.3.3-1 *Mechanical Properties of Thermoplastic Pipes*
Cell class for Corrugated PE Pipe—AASHTO M 294 to ASTM D 3350 335420C.	Cell class for Corrugated PE Pipe—AASHTO M 294 to ASTM D 3350 335400C with additional environmental stress crack resistance evaluation according to SP-NCTL test as set forth in AASHTO M 294.

APPENDIX A

QUESTIONNAIRE TO INQUIRE ON THE FIELD PERFORMANCE OF CORRUGATED HIGH DENSITY POLYETHYLENE PIPE SYSTEMS

Questionnaire No.1 - Request for General Information on Corrugated HDPE Pipe Installations

The purpose of Questionnaire No.1 is to establish your general experience with corrugated HDPE pipe. We are interested in the applications, sizes, depths of fill, and performance information. If you have a specific site where pipe(s) have cracked, please fill out Questionnaire No. 2 for that site. The source of the information will be kept confidential. (i.e., the specific site location, the manufacturer's name and the names of people offering information will not be identified in the project report.)

1) Application(s) of the pipe (check all that apply):

Culvert   Storm drain   Sanitary sewer   Cross drain   Side drain
Other (such as experimental research) ____________________

2) Diameter:
Minimum ____________ (in)   Maximum ____________ (in)

3) Approximate installed lengths for all your sites:
diameter less than or equal to 18 in ____________ (ft)
diameter greater than 18 in ____________ (ft)
installed before 1990 ____________ (ft)
installed after 1990 ____________ (ft)

4) Approximate burial depths for all your sites:
minimum depth of fill under roadways ____________ (ft)
minimum depth of fill without traffic ____________ (ft)
maximum depth of fill ____________ (ft)

5) What is your general experience with corrugated HDPE pipe:
Good   Satisfactory   Unsatisfactory
Comments:____________________

6) Regardless of your answer to question 5, have you encountered problems with corrugated HDPE pipes:

None   Deflections   Cracks   Joints   Buckling   Others____________

Comments: ____________________

7) Respondent information
Name____________   Telephone ____________
Organization ____________________
Address ____________________

8) If you are not the owner of the system
Owner contact____________   Telephone ____________
Organization ____________________
Address ____________________

Please fax this form to Grace Hsuan by March 28, 1997 at (215) 895-1437

If your have any questions you can contact:

Grace Hsuan
GRI/Drexel University
Rush Building- west wing
Philadelphia, PA 19104
Tel: (215) 895-2785
e-mail: ghsuan@coe.drexel.edu

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Simpson Gumpertz & Heger, Inc.
297 Broadway
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Tel : (617) 643-2040 (x240)
e-mail : tjmcgrath@sgh.com

Questionnaire No. 2 - Request for Information on Performance of Specific Installation with Corrugated HDPE Pipe
(please copy and use a separate form for each site)

The purpose of this questionnaire is to provide information on specific site where corrugated HDPE pipe has been installed and experienced cracking. The source of the information will be kept confidential. (i.e., the specific site location, the manufacturer's name and the names of people offering information will not be identified in the project report.)

1) Application of the pipe:

Culvert Storm drain Sanitary sewer Cross drain Side drain

Other (such as experimental research) ____

2) Location of the site: Town/City/State ____

Highway/Route/Exit ____

Street/Road ____

3) Year installed:__________________________

4) Structure above the pipe: Asphalt pavement Concrete pavement Unpaved roadway

Other ____

Pavement thickness: ______________________________

Average daily traffic: Heavy Medium Light

5) Type of backfill around the pipe: Gravel Sand Silt Clay Mixed

ASTM D 2487 Classification (if available) ____

6) Depth of fill above the pipe (from top of the pipe to ground surface):__________________ (ft)

7) Corrugation profile (check all that apply):

Corrugated interior Smooth interior

Corrugation type: Spiral Annular

8) Pipe inside diameter : ____________________(inch)

9) Pipe manufacturer or Distributor : ____

10) Total length of the pipe : __________ (ft)

11) Number of pipe sections: _________________

12) Availability of pipe material specification: yes , no

13) Availability of installation specification: yes , no

14) When was the pipe inspected?

date _________________ Frequency _______________

Documentation availability: Report Photos

15) Please give an assessment of the condition of the pipe system:

(a) Deflections? yes no

(i) number of readings taken: ____

(ii) location(s) with respect to the pipe end (east, west, north or south): ____________________

____

(iii) average vertical diameter:________________ (inch)

(iv) average horizontal diameter:______________ (inch)

(b) Buckling? yes no

(i) location(s) with respect to the pipe end (east, west, north or south): ____________________

____

(ii) circumferential position (use clock position when looking upstream):_________________________

____

(iii) approximate description: ____

____

(c) Splitting or Cracking? yes no

(i) number of cracks: ____

(ii) the range of crack lengths: min.____________ (inch) ; max. ___________ (inch)

(iii) location(s) with respect to the pipe end (east, west, north or south): ____________________

(iv) are all the cracks located in a particular section of the pipe? ____________________

(v) type of cracks: Circumferential cracks , number ___________________

Longitudinal cracks , number _______________

(vi) for corrugated pipes, describe locations of the cracks with respect to the pipe profile: ___________

(vii) other observations or comments: ____

(d) Problems at joints?

(i) approximate description: ____

(16) Are any of the cracked areas readily accessible for inspection? yes , no

(17) Will your department perform an inspection in the next three months? yes , no

(18) Can we obtain permission to visit the site and take samples for evaluation? yes , no

(19) Respondent information

Name________________________________ Telephone ____________________________

Organization ____

Address ____

(20) If you are not the owner of the system

Owner contact________________________ Telephone ____________________________

Organization ____

Address ____

Please fax this form to Grace Hsuan by March 28, 1997 at (215) 895-1437

If your have any questions you can contact:

Grace Hsuan
GRI/Drexel University
Rush Building- west wing
Philadelphia, PA 19104
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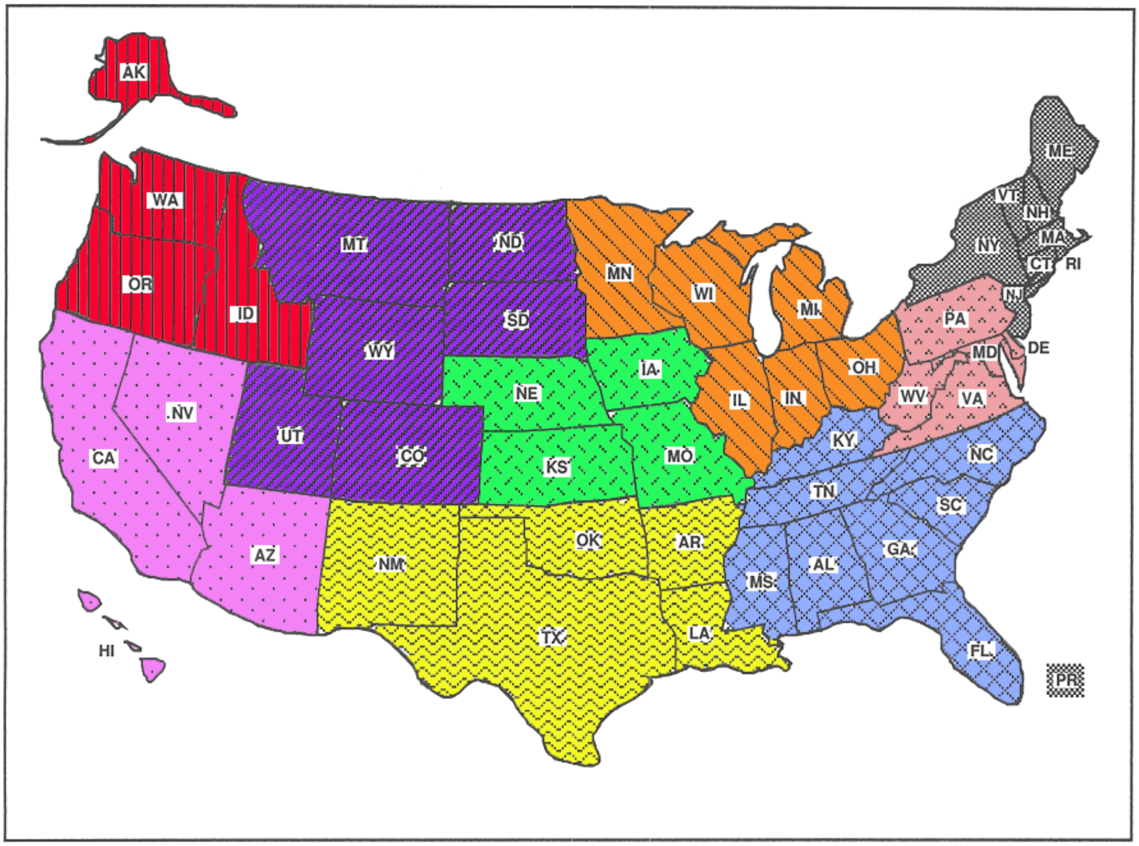
APPENDIX B

RESPONSES OF QUESTIONNAIRE

Table B-1 – Summary of Information from Questionnaire 1

Table B-2(I) – Basic Data from Questionnaire 2

Table B-2(II) – Additional Data from Questionnaire 2



Region 1 - CT, MA, ME, NH, NJ, NY, PR, RI, VT

Region 2 - DC

Region 3 - DE, MD, PA,. WV, VA

Region 4 - AL, FL, GA, KY, MS, NC, SC, TN

Region 5 - IL, IN, OH, MI, MN, WI

Region 6 - AR, LA, NM, OK, TX

Region 7 - IA, KS, MO, NE

Region 8 - CO, MT, ND, SD, UT, WT

Region 9 - AZ, CA, HI, NV

Region 10 - AK, ID, OR, WA

Note: Locations of organizations responding to Questionnaire No. 1 are reported based on the Federal Highway Administration (FHWA) Region in which they are located.

Figure B-1 - FHWA Regions

Table B-1 - Response of Questionnaire 1
(Questionnaire No. 1: Responses General Information on Corrugated HDPE Pipe Installation)

No.	Site Region	Application	Diameter (mm)		Installed Lengths (m)				Burial Depth (m)	General Experience with HDPE Pipes	Problems Experienced with HDPE Pipes
			Max.	Min.	< 450 mm Dia.	> 450 mm Dia.	Before 1990	After 1990			
1	Region 4	Culvert	900	450	na	na	na	na	na	Good	Deflections; Buckling (Deflection due to improper installation)
2	Region 4	Storm drain Experimental research	na	375	27	na	na	27	0.75 (min.) 0.9 (max)	na (Limited sites)	na (Still monitoring)
3	Region 5	Storm drain Culvert	750	300	300	30	150	180	0.45 (min.) 0.15 (min. no traffic) 1.5 (max.)	Satisfactory	Joints
4	Region 5	Storm drain	900	300	1500	1500	0	3000	0.6 (min.) 0.3 (min. no traffic) 3.6 (max.)	Unsatisfactory (Too fragile, easily damaged during installation)	Joints; Buckling
5	Region 1	Culvert Storm drain Cross drain Side drain	900	150	300 (375 mm)	300 (750 mm)	na	na	2.4 (min.) 1.2 (min. no traffic) 2.4 (max.)	Satisfactory (Limited experience)	na
6	Region 5	Culvert Storm drain Sanitary sewer Cross drain Side drain	900	150	na	na	na	na	0.9 (min.) 7.5 (max.)	Satisfactory	Deflections; Cracks; Joints Buckling
7	Region 6	Culvert Storm drain Sanitary sewer Cross drain Side drain	na	300	na	na	na	na	1.2 (min.) 0.45 (min. no traffic)	Good	Cracks (exposed end section of pipe probably can be damaged by mowing)
8	Region 1	Culvert Storm drain Cross drain Side drain	750	150	2100	270	0	na	0.9 (min.) 0.9 (min. no traffic)	Satisfactory	na
9	Region 1	Storm drain	750	450	996	180	na	all	1.5 (min.) 2.5 (max.)	Satisfactory	na
10	Region 6	Culvert Side drain	600	600	0	90 to 120	0	105	0.6 (min.) 0.3 (min. no traffic) 0.6 (max.)	Satisfactory (Concern silting problem difficult to clean the corrugated wall)	na

Note : na = non-available (i.e., information was not provided)

Table B-1 - Continue

No.	Site Region	Application	Diameter (mm)		Installed Lengths (m)				Burial Depth (m)	General Experience with HDPE Pipes	Problems Experienced with HDPE Pipes
			Max.	Min.	< 450 mm Dia.	> 450 mm Dia.	Before 1990	After 1990			
11	Region 4	Culvert Storm drain	900	450	na	300	na	300	1.5 (min.) 0.9 (min. no traffic) 4.5 (max.)	Satisfactory	na (Poor backfill can cause misalignment of pipes)
12	Region 4	Culvert Cross drain Side drain	450	300	15	na	na	105	0.6 (min.) 3.6 (max.)	Good	na
13	Region 4	Culvert Cross drain Side drain	450	375	12	12	na	na	0.45 (min.) 0.6 (max.)	na (Just started, too early to provide information)	na
14	Region 10	Culvert	900	300	na	na	na	na	1.2 (min.) 3.6 (max.)	Satisfactory	na
15	Region 3	Culvert Storm drain Cross drain Side drain Exp. research	1200	100	na	na	na	na	0.45 (min.) 0.45 (min. no traffic) 12 (max.)	Good (HDPE pipe is mostly used in maintenance work)	Deflections; Crack; Joints (difficult to maintain alignment) (see Questionnaire 2)
16	Region 10	Culvert Storm drain Experimental use in subdrain behind structure	1200	450	1590	750	0	2340	0.6 (min.) 0.6 (min. no traffic) 4.5 (max.)	Good	na (Contractors taking advantage of lower material & installation costs in the 450 mm and 600 mm pipes)
17	Region 5	Storm drain	900	375	na	na	na	300	0.6 (min.) 4.5 (max.)	Unsatisfactory	Deflections; Joints; Buckling (pipes can be damaged during installation)
18	Region 5	Culvert Storm drain	450	300	3600	na	na	3600	1.2 (min.) 1.2 (min. no traffic) 3 (max.)	Good/Unsatisfactory (good for entrance culverts; not suitable for storm sewer and under roadway)	Deflections; Cracks; Joints Buckling; Crushed (replace 30-40% of pipes due to above problems) (see Questionnaire 2)
19	Region 1	Culvert	1200	375	1077	98	74	1101	0.9 (min.) 0.45 (min. no traffic) 3 (max.)	Good (Some seam cracked due to transportation)	na (currently cannot inspect the pipes due to snow cover and ice)
20	Region 5	Culvert Storm drain Cross drain Side drain	1350	300	9600	2854	60	12394	0.3 (min) 0.3 (min. no traffic) 4.5 (max.)	Good	na (Not every new pipe has been inspected after installation)
21	Region 1	Culvert Storm drain	900	375	300	600	na	900	0.3 (min.) 1.2 (max.)	Satisfactory	Deflections

Note : na = non-available (i.e., information was not provided)

Table B-1 - Continue

No.	Site Region	Application	Diameter (mm)		Installed Lengths (m)				Burial Depth (m)	General Experience with HDPE Pipes	Problems Experienced with HDPE Pipes
			Max.	Min.	< 450 mm Dia.	> 450 mm Dia	Before 1990	After 1990			
22	Region 6	Storm drain	900	600	na	2400	na	2400	0.3 (min) 0.3 (min. no traffic) 4.5 (max.)	Satisfactory	Deflections; Crack; Joints (Most problems occurred in the handling and installation)
23	Region 6	Culvert Cross drain	600	600	na	266	na	266	0.3 (min) 0.3 (min. no traffic) 0.36 (max.)	Good	na
24	Region 8	Cross drain Side drain	na	450	na	300	300	na	na	Satisfactory (haven't used much and none installed recently)	na
25	Region 4	Culvert Storm drain	1200	300	12	25	na	na	1.2 (min) 0.3 (min. no traffic) 2.4 (max.)	Satisfactory	Deflections; Buckling
26	Region 8	Culvert Storm drain	900 since 1987, over 300 m	375	na	na	na	na	na	Satisfactory (results varied from good to not so good)	Deflections; Cracks; Joints (see Questionnaire 2)
27	Region 1	Storm drain Side drain Experimental basis for cross drain	900	na	na	na	na	na	na	Satisfactory	Deflections; Cracks; Buckling One pipe under roadway had failed (see Questionnaire 2)
28	Region 6	Storm drain	na	na	na	na	na	na	na	na	Cracks (see Questionnaire 2)
29	Region 7	Culvert Storm drain Sanitary sewer Side drain	na	150	15000	limited	7500	7500	0.9 (min. no traffic) 1.8 (max.)	Satisfactory	Calcium carbonate deposits (see Questionnaire 2)
30	Region 4	Storm drain Cross drain Side drain	750	375	840	1800	na	2640	1.2 (min) 0.6 (min. no traffic) 2.4 (max.)	Satisfactory	Deflections; Cracks; Joints (most deflections are related to installation) (see Questionnaire 2)
31	Region 5	Storm drain	900	300	120 to 150	240 to 300	0%	100%	0.9 (min) 0.6 (min. no traffic) 1.8 (max.)	Good	None

Note : na = non-available (i.e., information was not provided)

Table B-1 - Continue

No.	Site Region	Application	Diameter (mm)		Installed Lengths (m)				Burial Depth (m)	General Experience with HDPE Pipes	Problems Experienced with HDPE Pipes
			Max.	Min.	< 450 mm Dia.	> 450 mm Dia.	Before 1990	After 1990			
32	Region 1	Sanitary sewer	750	750	na	600	0	600	1.8 (min. no traffic) 6 (max.)	Unsatisfactory (most problems associated with installation)	Deflections; Cracks; Joints and Buckling (Pipe floated during installation due to poor backfill) (see Questionnaire 2)
33	Region 1	Culvert Storm drain	600	300	450	1050	na	1500	0.45 (min) 0.6 (min. no traffic) 1.5 (max.)	Good (easily installed lightweight)	none
34	Region 4	Storm Drain	na	600	na	na	na	na	0.3 (min. no traffic) 0.3 (max.)	Unsatisfactory	Cracks; Buckling (retrieved sections were cracked and buckling) (see Questionnaire 2)
35	Region 10	Storm Drain	600	200	2998	1031	none	4029	7.5 (max.)	Satisfactory/unsatisfactory	Joints (bands for joints in 600 mm dia. under designed, led to coupling breaking and pipes float to the surface)
36	Region 1	Culvert Storm drain	900	150	600	300	none	none	0.6 (min.) 0.3 (min. no traffic) 1.2 (max.)	Unsatisfactory	Deflections; Joints; Buckling (see Questionnaire 2)
37	Region 7	Culvert Storm drain	900	300	na	na	na	na	0.6 (min.) 0.6 (min. no traffic) 3 (max.)	na (performance of installed pipes has not been checked)	Cracks; Buckling (see Questionnaire 2)
38	Region 5	Storm drain Sanitary sewer	1050	200	2370	600	570	2400	0.6 (min.) 2.4 (min. no traffic) 2.1	Good	None

Note: na = non-available (i.e., information was not provided)

Table B-1 - Continue

No.	Site Region	Application	Diameter (mm)		Installed Lengths (m)				Burial Depth (m)	General Experience with HDPE Pipes	Problems Experienced with HDPE Pipes
			Max.	Min.	< 450 mm Dia.	> 450 mm Dia.	Before 1990	After 1990			
39	Region 5	Sanitary sewer	600	600	na	114	na	114	2.1 (min. no traffic) 3.9 (max.)	Satisfactory	None (Pipe is part of a sanitary system and is not observable but there are no physical signs of failure)
40	Region 5	Culvert Storm drain Cross drain Side drain	750	300	900	90	na	990	0.6 (min.) 0.3 (min. no traffic) 3 (max.)	Satisfactory	Deflections (proper backfill is critical)
41	Region 9	Storm drain	na	600	na	180	na	na	3.6 (min.)	Good	None
42	Region 5	Culvert Storm drain	1200	300	1500	900	na	2400	0.6 (min. no traffic) 2.4 (max.)	Good	Deflections
43	Region 4	Storm drain Cross drain Side drain	900	300	na	232	40	192	0.6 (min.) 0.45 (min. no traffic) 6 (max.)	Good	Deflections; Joints (problems are not major; pipe systems are still working satisfactorily) (see Questionnaire 2)
44	Region 5	Storm drain Sanitary drain	450	200	2400	0	0	2400	1.5 (min.) 2.25 (min. no traffic) 6 (max.)	Satisfactory	None
45	Region 10	Culvert Storm drain Cross drain Side drain Side drain	1200 for culverts 600 for Storm drain	300	25500	3000	0%	100%	0.6 (min.) 0.3 (min. no traffic) 4.5 (max.)	Good	None (no formal inspection has been performed on the pipes)
46	Region 10	Wet land distribution piping	600	200	3255	1020	na	4275	2.4 (min.) 0.3 (min. no traffic) 2.4 (max.)	Marginally Satisfactory (Floated to top of burial)	Joints (Joints failed; pipe floated)

Note: na = non-available (i.e., information was not provided)

Table B-1 - Continue

No.	Site Region	Application	Diameter (mm)		Installed Lengths (m)				Burial Depth (m)	General Experience with HDPE Pipes	Problems Experienced with HDPE Pipes
			Max.	Min.	< 450 mm Dia.	> 450 mm Dia.	Before 1990	After 1990			
47	Region 10	Culvert Sanitary sewer Cross drain Side drain Leachate and Gas collection	900	200	18000	4500	12000	6000	0.9 (min) 84 (max)	Satisfactory	None
48	Region 5	Storm drain Cross drain Side drain	750	300	705	302	784	223	na	Satisfactory	None
49	Region 5	Culvert Storm drain Cross drain Side drain	600	300	4200	300	0	4500+	0.9 (min.) 0.3 (min. no traffic) 3 (max.)	Good (Easy install, excellent flow characteristics)	None (only use "S" type pipes)
50	Region 5	Culvert	1200	300	480	288	0%	100%	0.2 (min.) 2.4 (max.)	Satisfactory (Easy to install, excellent flow characteristics)	Deflections; Buckling (Probably due to installation, i.e., poor compacting, etc.)
51	Region 3	Culvert Storm drain Cross drain Side drain	24	100	1425	144	na	na	0.6 (min.) 0.3 (min. no traffic) 4.5 (max.)	Satisfactory (Max. 600 mm diameter, not allowed under major national highway)	Deflections; Cracks; Buckling
52	Region 5	Culvert Storm drain Cross drain Side drain	600 (standard) 750 & 900 (culvert)	100 (under drain & sewer) 300 (culvert)	total 60000 + meters				0.9 (min.) 0.6 (min. no traffic) 3 (max.)	Satisfactory	Deflections; Joints
53	Region 1	Culvert Storm drain	450	300	1222	na	0%	100%	0.9 (min.) 0.75 (min. no traffic) 2.4 (max.)	Satisfactory (Not recommend using this pipe in roadway areas, but slope drains are possible)	None (Install the pipe need extra time & effort which is not good for limited stage and operations.)
54	Region 5	Storm drain	450	300	600	na	na	na	3 (min.) 0.6 (min. no traffic) 4.2 (max.)	Good	None (all pipes were placed in 1996 and there were no problems during installation)
55	Region 5	Culvert Storm drain	1050	300	360	240	150	450	0.9 (min.) 0.6 (min. no traffic) 3 (max.)	Good	None

Note: na = non-available (i.e., information was not provided)

Table B-1 - Continue

No.	Site Region	Application	Diameter (mm)		Installed Lengths (m)				Burial Depth (m)	General Experience with HDPE Pipes	Problems Experienced with HDPE Pipes
			Max.	Min.	= 450 mm Dia.	> 450 mm Dia.	Before 1990	After 1990			
56	Region 5	Culvert Storm drain Sanitary sewer Side drain	1050	na	1500	900	600	1800	0.6 (min.) 0.6 (min. no traffic) 3.6 (max.)	Good	Buckling (Pipes were damaged due to shallow depth)
57	Region 9	Culvert Storm drain Cross drain Side drain	900	450	na	na	na	na	0.6 (min.) 0.6 (min. no traffic) 3.3 (max.)	Satisfactory (very limited experience with HDPE pipes)	na
58	Region 9	Storm drain Sanitary sewer	900	300	180	1200	0	1380	0.6 (min.) 1.5 (min. no traffic) 6.9 (max.)	Good (no long term experience, but short term has no problems.)	None
59	Region 3	Storm drain	900	375	3000	600	very little	most all	0.3 (min. no traffic) 2.1 (max.)	Satisfactory	Deflections; Joints; Buckling (Problems were with Type "C" Pipes)
60	Region 4	Cross drain Side drain	600	450	108	11	0	119	0.6 (min.) 0.9 (max.)	Satisfactory	None
61	Region 9	Sanitary Sewer	300	na	90	na	0	na	1.8 (max.)	Satisfactory	Deflections
62	Region 5	Culvert Storm Drain	900	300	600+	90	0	na	0.3 - 0.6 (min.) 0.3 (min. no traffic) 2.4 - 3 (max.)	Fair (Experienced some failures)	Deflections; Cracks, Joints; Buckling
63-1	Region 4	Cross Drain Side Drain	900	375	3702	1356+	48	5010	0.3 (min.) 0.3 (min. no traffic)	Good (Evaluated and recom. approval of HDPE corrugated and Type S pipes.)	None
63-2	Region 4	Side Drain	600	375	1140	390	na	1530	0.3 (min. no traffic)	Good	None
63-3	Region 4	Side Drain	900	450	120	150	na	270	0.6 (min.) 1.5 (max.)	Good	None
63-4	Region 4	Side Drain	900	450	750+	600+	na	1350	0.3 - 0.6 (min.) 1.5 - 1.8 (max.)	Good	None

Note: na = non-available (i.e., information was not provided)

Table B-1 - Continue

No.	Site Region	Application	Diameter (mm)		Installed Lengths (m)				Burial Depth (m)	General Experience with HDPE Pipes	Problems Experienced with HDPE Pipes
			Max.	Min.	= 450 mm Dia.	> 450 mm Dia.	Before 1990	After 1990			
63-5	Region 4	Side Drain Storm Drain	900	375	1500	0	0	1500	0.45 (min.) 0.15 (min. no) traffic) 1.8 - 2.4 (max.)	Good (Light weight; easy to handle. Concerned that exposed ends may damaged due to equipment)	None (the exposed ends which can be damaged by mowing.)
63-6	Region 4	Cross Drain Side Drain	600	450	12	36	48	0	na	Satisfactory (Side Drain pipe lengths are not included in totals.)	Cracks (Care must be take to prevent deflection. Exposed end may be damaged by mowing.)
63-7	Region 4	Culvert Side Drain	600	375	180	180	0	360	0.6 (min.) 1.5 (min. no traffic) 1.5 (max)	Good (Easy to install with minimal labor and equipment.)	None
64	Region 9	Sanitary Sewer	1200	na	0	450	0	450	4.5 (max.)	Satisfactory	Deflections (Non uniform deflections, none exceeding limits.)
65	Region 10	Culvert Storm Drain Cross Drain Side Drain	900	100	600+	300+	300	300	0.9 (min.) 0.3 (min. no traffic) 4.5 (max.)	Satisfactory	Joints; Buckling (Only in 100 mm pipe due to shallow installation and construction equipment crushing the pipe.)
66	Region 5	Culvert Storm Drain	375	300	750	0	0	750	0.9 (min.) 0.9 (min. no traffic) 2.1 (max.)	Satisfactory	None
67	Region 6	Side Drain	900	450	2600	1307	0	3908	na	Good (All PE pipe has been installed by State Maintenance forces.)	None
68	Region 5	Culvert Side Drain	900	100	17310	6120	11460	11970	0.3 (min.) 0.3 (min. no traffic) 3 (max.)	Satisfactory	na
69	Region 9		600	300	0	0	0	1650	3.6 (min. no traffic) 4.5 (max.)	Unsatisfactory	Deflections, Cracks, Joints; Buckling (see Questionnaire 2)

Note: na = non-available (i.e., information was not provided)

Table B-1 - Continue

No.	Site Region	Application	Diameter (mm)		Installed Lengths (m)				Burial Depth (m)	General Experience with HDPE Pipes	Problems Experienced with HDPE Pipes
			Max.	Min.	= 450 mm Dia.	> 450 mm Dia.	Before 1990	After 1990			
70	Region 10	Culvert	450	300	9 to 12	12 to 18	na	na	0.6 (min.) 0.3 (min. no traffic) 1.5 (max.)	Good (Good flow characteristics. Unsure of longevity and wear.)	None
71	Region 6	Culvert Side-drain	900	600	na	na	na	na	0.6 (min.) 2.4 (max.)	na	Deflections, Cracks; Buckling
72	Region 5	Culvert Sanitary sewer Cross drain Side drain	1500	100	Data recording started from 1996, 26,250 m installed in 1996				0.3 (min.) 0.45 (min. no traffic) < 3 (max.)	Good	Deflections; Cracks; Joints; Buckling (see Questionnaire 2)
73-1	Region 4	Culvert Storm Drain	750	300	na	45	0%	100%	3 to 4.5 (no traffic) 6 (max.)	Unsatisfactory	Deflections; Joints (Most problems attributed to poor method of on-site construction (see Questionnaire 2)
73-2	Region 4	Storm Drain	750	300	150	30	0%	100%	0.9 (min.) 0.9 (min. no traffic) 2.4 (max.)	Unsatisfactory (Do not get good results unless fully following ASTM D 2321 procedures)	Deflections; Joints; Cracks (Possibly due to non-compliance with ASTM D 2321) (see Questionnaire 2)
74	Region 3	Culvert Storm Drain	750	300	150	60	0	na	3.6 (min.) 3.6 (min. no traffic)	Unsatisfactory (Pipe separates from inside-out)	Cracks (see Questionnaire 2)
75	Region 7	Culvert	1050	300	6	6	na	na	0.3 (min.) 0.3 (min. no traffic) 1.8 (max.)	Satisfactory	Joints
76	Region 1	Culvert Storm Drain	900	300	50%	50%	18,000	135,000	0.3 (min.) 0.3 (min. no traffic) 4.5 (max.)	Good (The use of PE pipe has increased over the past 5 years)	(Quality Control and some handling and storage problems. Materials details have since been required to alleviate these problems)
77	Region 10	Storm Drain	750	600	0	360	na	na	0.3 (min. no traffic) 0.9 (max.)	Good	None

Note: na = non-available (i.e., information was not provided)

Table B-1 - Continue

No.	Site Region	Application	Diameter (mm)		Installed Lengths (m)				Burial Depth (m)	General Experience with HDPE Pipes	Problems Experienced with HDPE Pipes
			Max.	Min.	= 450 mm Dia.	> 450 mm Dia.	Before 1990	After 1990			
78	Region 5	Culvert	900	150	23170	4650	2,310	25,500	0.3 to 0.6 (min.) 6 (min. no traffic) 6 (max.)	Satisfactory (Joints have problems)	Joints (Joint has a tear in it) (see Questionnaire 2)
79	Region 9	Sanitary sewer	600	na	na	269	na	na	4.2 (min.) 5.1 (max.)	Satisfactory	Buckling (see Questionnaire 2)
80	Region 4	Side Drain	900	375	3330	900	na	na	0.3 (min. no traffic) 3 (max.)	Good	None
81	Region 9	Culvert Storm drain Cross drain Side drain	900	100	na	na	na	na	0.6 (min.) 9 (min. no traffic) 9 (max.)	Good (Easy to install. Only have six years experience, no long term data)	Joints (Difficult to get tight joints with spiral corrugated pipe. We require neoprene gasket)
82	Region 5	Storm drain Sanitary sewer Side drain	375	100	na	na	na	all	0.6 (min.) 0.6 (min. no traffic) 3.3 (max.)	na (Not enough HDPE Installed to establish case histories)	None
83	Region 10	Culvert Storm drain	900	100	450	150	na	100%	0.3 (min.) 0.15 (min. no traffic) 6 (max.)	Satisfactory	None
84	Region 6	Storm drain	900	450	60	300	300	60	1.2 (min. no traffic) 1.8 (max.)	Unsatisfactory (Joints came apart; cracks in pipe, Deflections.)	Joints; Cracks; Deflections (see Questionnaire 2)
85-1	Region 4	Culvert Storm drain Cross drain	750	250	300	150	0	100%	0.3 (min.) 0.3 (min. no traffic) 0.9 (max.)	Good	Crack (see Questionnaire 2)
85-2	Region 4	Storm drain	450	375	12	0	0	100%	0.6 (min.) 1.2 (max.)	Good	None
85-3	Region 4	Storm drain Side drain	1200	375	7	30	0	na	0.3 (min. no traffic) 1.8 (max.)	Good	None

Note: na = non-available (i.e., information was not provided)

Table B-1 - Continue

No.	Site Region	Application	Diameter (mm)		Installed Lengths (m)				Burial Depth (m)	General Experience with HDPE Pipes	Problems Experienced with HDPE Pipes
			Max.	Min.	= 450 mm Dia.	> 450 mm Dia.	Before 1990	After 1990			
85-4	Region 4	Culvert Side drain	600	300	180	60	0	100%	0.3 (min. no traffic) 3 (max.)	Satisfactory (needs a min. of 300 mm of cove some flexibility allows pipeline to be turned without constructing a junction box)	Deflection; buckling (problems when occur less than 300 mm of cover is used, or proper compacting is not performed around sidewalls).
85-5	Region 4	Storm drain Cross drain	1500	1500	0	45	0	100%	1.8 (min.) 1.8 (min. no traffic) 1.8 (max.)	Unsatisfactory (Buckling is a problem)	Deflection; Buckling (see Questionnaire 2)
86	Region 5	Cross drain	600	600	0	24	100%	0%	0.6 - 0.9 (max.)	Good	None
87	Region 10	Culvert Storm drain Cross drain	900	300	3200 to 7900 meters		0%	100%	0.3 (min.) 3 (max.)	Good	None (problems with ends of culverts floating or lifting up causing problems with the flowing water).
88	Region 7	Storm drain	375	375	na	na	na	na	0.45 (min.) 0.45 (min. no traffic)	Satisfactory	Buckling (due to construction activity)
89	Region 10	Storm drain	450	450	na	na	na	32	na	na	Buckling; Cracks; Joints (see Questionnaire 2)
90	Region 5	Culvert Cross drain	1050	450	300	18	na	na	0.6 (min.) 0.6 (min. no traffic) 6 (max.)	Good	Deflection ; Joints (see Questionnaire 2)
91	Region 4	Culvert Storm drain Sanitary sewer Cross drain Side drain	600	100	na	na	na	na	1.2 (min.) 0.3 (min. no traffic) 6 (max.)	Satisfactory (good in drain but poor in sanitary applications)	Joints (problem in passing an air test)
92	Region 4	Storm drain Cross drain Side drain	450	150	90	na	na	90	0.9 (min.) 0.9 (min. no traffic) 3 (max.)	Satisfactory	Deflections (during installation)
93	Region 1	Culvert	900	300	18	90	0	108	.025-0.15 (min.) 1.5 (max.)	Good (limited experience)	Deflections, Cracks, Joints (see Questionnaire 2)

Note: na = non-available (i.e., information was not provided)

Table B-1 - Continue

No.	Site Region	Application	Diameter (mm)		Installed Lengths (m)				Burial Depth (m)	General Experience with HDPE Pipes	Problems Experienced with HDPE Pipes
			Max.	Min.	= 450 mm Dia.	> 450 mm Dia.	Before 1990	After 1990			
94	Regions 8, 9 & 10	Agricultural drain. Toe drainage for dams and canals	1050	100	3000000	10500	2E+06	600000	0.3 (min.) 0.3 (min. no traffic) 6 (max.)	Good (limited experience)	Deflections, Buckling
95	Region 3	Culvert Storm drain	900	150	13500	3300	na	all	0.3 (min.) 0.3 (min. no traffic) 3 (max.)	Good	none
96	Region 8	Culvert Storm drain Cross drain	900	300	na	na	na	na	0.3 (min.) 0.3 (min. no traffic) 11 (max.)	Satisfactory (proper installation important to the performance)	Cracks, Buckling (Attributable to installation deficiency, damaged pipes have been replaced)
97	Region 7	Culvert Side drain	750	100 or 375	20	315	na	all	0.3 (min.) 1.5 (max.)	Good for Culvert Unsatisfactory for side drain & outlet	Deflections, Buckling (for side drain and outlet, due to poor installation)
98	Region 1	Storm drain	900	150	na	na	na	na	na	Satisfactory (concern on the installation)	Deflection, Cracks, Joints, Buckling (Attributable to installation deficiency)
99	Region 4	Culvert Side drain Cross drain	1200	100	thousands				0.3 (min. no traffic) 6 (max.)	Satisfactory (Performance dependent on backfill)	Deflection, Cracks, Joints, Buckling (largely contributed by the improperly backfill) (see Questionnaire 2)
100	Region 8	Storm drain	1200	450	300	> 3000	450	> 3000	0.9 (min.) 0.3 (min. no traffic) 2.4 (max.)	Satisfactory	Deflection, Cracks, Joints, Buckling (see Questionnaire 2)
101	Region 5	Storm drain Culvert	1200	300	6000	1500	0	7,500	0.3 (min.) 0.3 (min. no traffic) 9 (max.)	Unsatisfactory Large pipes have cracks	Deflection, Cracks, Buckling (see Questionnaire 2)
102	Canada	Cross drain	900	150	na	na	na	na	0.1 (min.) 9 (max.)	na	Deflection (see Questionnaire 2)
103	Region 10	Cross drain	1200	450	4500 since 1988				0.6 (average)	Good	Cracks (see Questionnaire 2)

Note: na = non-available (i.e., information was not provided)

Table B-2 (I) - Response of Questionnaire 2 (Part I)

(Questionnaire No. 2: Responses for Information on Performance of Specific Installation with Corrugated HDPE Pipe)

No.	Site Region	Application	Year Installed	Structure Above the Pipe	Pavement Thickness (mm)	Daily Traffic	Type of Backfill	Depth of Backfill (m)	Corrugation Profile	Inside Diameter (mm)	Total Pipe Length (m)	No. Pipe Sections	Specification	Pipe Inspection		
														Date	Frequency	Document
15	Region 3	Experimental	1987	na	na	na	Gravel	30	Smooth & Corrugated interior spiral	600	180	30	none	91, 92, 93 94, 95 & 97	1	Reports Photos
18	Region 5	Storm drain	1992	Asphalt pavement	150 and 150 aggregate	Medium	sand	0.6 to 1.2	Smooth interior Annular	450 to 900	1800	300	none	1992	during construction	na
26	Region 8	Rundown	1993+	Soil	na	na	na	0.3 to 0.6	Smooth interior Annular	1200	60	na	material installation	summer 1996	na	Photos
27	Region 1	Culvert	1991+	Asphalt pavement	na	Light	sand	2.4 to 3	Smooth interior	900	21	4	none	1996	na	Photos
28-1	Region 6	Storm drain	1994	Soil	150	na	sand	1.2 to 2.4	Smooth interior Spiral	900	1500	250	material installation	1994	na	none
28-2	Region 6	Storm drain	1994	Soil	na	na	na	1	Smooth interior Spiral	600	na	na	none	1997	na	Photos
29	Region 7	Culvert Storm drain Sanitary sewer Side drain	1980	Asphalt pavement Concrete pavement	250 to 375	Heavy	Gravel	na	Corrugated & Smooth Interior Annular	150+	60	10	material installation	na	na	none
30	Region 4	Storm drain Cross drain	1994	Asphalt pavement	75	Medium	Mixed	0.9 to 1.5	Smooth Interior Annular	750	36	6	installation	4/21/94	na	Report
32	Region 1	Sanitary sewer	1991	Soil (right of way)	na	na	Gravel	1.8 to 3.6	Smooth Interior Spiral	750	600	11	none	1991	Daily	Report & Photos
34	Region 4	Storm drain	1995	Yard area	na	Light	Mixed	0.3	Smooth Interior	600	90	unknown	none		na	Report
36	Region 1	Storm drain	1991-1992	Asphalt pavement unpaved roadway	75	Light	ASTM D2487 #S3 stone	0.6	Smooth Interior	300 to 900	300	100	material installation	93 to 97	2 years	Photos
37	Region 7	Storm drain	late 1980	Concrete pavement	na	Medium	Gravel	1.5?	Smooth Interior	900	72	1		1993	once	none
43-1	Region 4	Cross drain	1993	Unpaved roadway	na	Heavy	Sand Clay Mixed	0.3	Smooth Interior Annular	750	24	4	material	Jun-93 Jul-93 Oct-93 Jan-94	same as date information	Report
43-2	Region 4	Cross drain	1988	Unpaved 1988-89 Paved from 1989 to present	100	Light	Mixed Clayey sand	0.6	Smooth Interior Spiral	600	40	6	material installation	May-90 Jul-90 Nov-90 Oct-92	same as date information	Report
43-3	Region 4	Storm drain	1992	Unpaved road	na	no traffic	clay	0.3 to 1.5	Smooth Interior Spiral	600	168	28	material installation	Aug-95	one inspection only	Photo-Video
43-4	Region 4	Cross drain	1994	Soil	na	no traffic	na	0.3 to 1.5	Smooth Interior Spiral	900	na	na	none	1997	na	Photo
43-5	Region 4	Cross drain	1994	Unpaved road	na	light but heavy	na	0.3 to 1.5	Smooth Interior Spiral	900	20	3	none	1997	na	Photo
43-6	Region 4	Storm drain	1995	Asphalt pavement	na	no traffic	na	0.6 to 1.2	Smooth Interior honeycomb	1050						
65	Region 8	Storm drain	1990	Asphalt pavement & unpaved road	na	no traffic	silt	1.5	Smooth interior Annular	450	120	na	material installation	1994	na	Photo

Note: na = nonavailable (i.e., information was not provided)

Table B-2(I) - Continue

No.	Site Region	Application Location	Year Installed	Structure Above the Pipe	Pavement Thickness (mm)	Daily Traffic	Type of Backfill	Depth of Backfill (m)	Corrugation Profile	Inside Diameter (mm)	Total Pipe Length (m)	No. Pipe Sections	Specification	Pipe Inspection Date	Pipe Inspection Frequency	Pipe Inspection Document
69	Region 9	Seepage interceptor perforated	na	Unpaved road	na	light	gravel/ sand	4.5	Smooth interior Annular	300 to 600	1650	na	material installation	yearly for 3 years	na	Photos
71	Region 6	Culvert	1994	7 m under live load the rest under a traffic island and outside of the road	na	light	flowable fill	0.6 to 1.2	Smooth interior spiral	900	60	2	possible	1996	once	Report & Photos
72-1	Region 5	Culvert	1995	na	na	na	na	na	Corrugated interior	600	6	1	material	1997	na	Photos
72-2	Region 5	Culvert	1994	Asphalt pavement	425	light	gravel #57 limestone	19.5	Smooth interior annular	1050	146	25	material installation	1996	yearly	Photos
72-3	Region 5	Culvert	1984	Asphalt pavement	375	light	gravel & sand ODOT 304	0.9 to 1.8	Corrugated interior	600	15	3	material installation	1997	8 year	Report & Photos
72-4	Region 5	Culvert	1985	Asphalt pavement	375	light	gravel & sand ODOT 304	0.6 to 1.2	Corrugated interior	375	12	3	material installation	1997	na	Photos
72-5	Region 5	Culvert	1982	Asphalt pavement	375	light	gravel & sand ODOT 304	0.3	Corrugated interior	375	12	2	material installation	1997	na	Photos
72-6	Region 5	Culvert	1983	Asphalt pavement	375	light	ash and rock	1.1	Corrugated interior	375	12	2	material	1997	na	Photos
72-7	Region 5	Culvert	1983	Asphalt pavement	375	light	gravel ODOT 8	0.6 to 1.2	Corrugated interior	375	12	2	material	1997	na	Photos
72-8	Region 5	Culvert	<1985	Asphalt pavement	na	light	granular & native soil	1.2	Corrugated interior	450	12	2	material	1997	na	Photos
72-9	Region 5	Culvert	<1985	Asphalt pavement	na	light	granular & native soil	0.9	Corrugated interior	375	12	2	material	1997	na	Photos
72-10	Region 5	Culvert	1983	Asphalt pavement	375	medium	gravel & sand ODOT 304	0.6	Corrugated interior	300	12	2	material installation	1997	na	Photos
72-11	Region 5	Culvert	1981	Asphalt pavement	375	light	gravel Bank run ODOT 304	<0.3	Corrugated interior	600	12	2	material installation	1997	na	Photos
72-12	Region 5	Culvert	1997	Asphalt pavement	375	light	annular rock & silt	3.0	Smooth Interior Spiral	900	7.5	2	material	1997	na	Photos
72-13	Region 5	Culvert	1983	Asphalt pavement	na	medium	ODOT 304	0.3	Corrugated Interior	450	12	2	material	1997	na	Photos
72-14	Region 5	Culvert	1983	Asphalt pavement	na	medium	ODOT 304	0.6	Corrugated Interior	450	12	2	material	1997	na	Photos
72-15	Region 5	Culvert	1983	Asphalt pavement	na	medium	ODOT 304	0.9	Corrugated Interior	450	12	2	material	1997	na	Photos

Note: na = nonavailable (i.e., information was not provided)

Table B-2(I) - Continue

No.	Site Region	Application Location	Year Installed	Structure Above the Pipe	Pavement Thickness (mm)	Daily Traffic	Type of Backfill	Depth of Backfill (m)	Corrugation Profile	Inside Diameter (mm)	Total Pipe Length (m)	No. Pipe Sections	Specification	Pipe Inspection		
														Date	Frequency	Document
72-16	Region 5	Culvert	1985	Asphalt pavement	375	light	gravel	0.6 to 0.9	Corrugated Interior	375	12	2	material	1997	na	Photos
72-17	Region 5	Culvert	1983	Asphalt pavement	na	Medium	ODOT 304	0.6	Corrugated Interior	600	12	2	material	1997	na	Photos
72-18	Region 5	Culvert	1984	Asphalt pavement	na	Light	ODOT 411 limestone	1.5	Corrugated Interior	300	12	2	material	1997	na	Photos
72-19	Region 5	Culvert	1982	Asphalt pavement	375	Light	gravel	1.35 to 1.8	Corrugated Interior	375	12	2	material	1997	na	Photos
72-20	Region 5	Culvert	1984	Asphalt pavement	375	Light	gravel & sand ODOT 304	0.9	Corrugated Interior	375	12	2	material installation	1997	na	Photos
72-21	Region 5	Culvert	1983	Asphalt pavement	375	Light	mixed	1.2	Corrugated Interior	375	13.5	3	material	1997	na	Photos
72-22	Region 5	Culvert	1983	Asphalt pavement	na	Light	mixed	0.3	Corrugated Interior	375	12	2	material installation	1997	na	Photos
73-1	Region 4	Storm Drain	1990	Unpaved roadway	na	None	mixed	<3	Smooth Interior Spiral	750	45	10 to 15	none	na	na	na
73-2	Region 4	Storm Drain	1995	Unpaved roadway	none	None	sand	2.4	Smooth Interior Annular	750	18	5	installation	1995	Irregular	Report
74	Region 3	Culvert Storm Drain	1996	Unimproved surface	na	None	mixed	1.2 to 1.8	Smooth Interior Spiral	750	45	6	none	1996	na	na
78-1	Region 5	Culvert	1994	Asphalt pavement	150	Medium	unknown	0.9	Smooth Interior	1050	18	na	material installation	1996	Annually	na
78-2	Region 5	Culvert	1996	Asphalt pavement	150	Medium	sand	3.3	Smooth Interior	1350	30	na	material installation	1996	Annually	na
79	Region 9	Sanitary sewer	1989	Unpaved Roadway	na	Medium	mixed	5.1	Smooth Interior Spiral	450	269	44	none	1989	na	na
84	Region 6	Storm drain	1989	Asphalt Pavement	na	na	clay	1.2	Smooth Interior	450	360	na	material installation	1996	na	Photos
85-1	Region 4	Storm drain	1993	na	na	na	na	na	Smooth interior spiral	750			none	1997	na	na
85-5	Region 4	Storm drain Cross drain	1993	Asphalt Pavement	100	na	clay	1.2	Smooth interior spiral	1500	36	6	material installation	1993 & 1994	12 months apart	na
89	Region 10	Storm drain Cross drain	1993	Asphalt Pavement	100	na	clay	1.2	Smooth interior spiral	1500	36	6	material installation	1993 & 1994	12 months apart	na

Note: na = nonavailable (i.e., information was not provided)

Table B-2(I) - Continue

No.	Site Region	Application	Year Installed	Structure Above the Pipe	Pavement Thickness (mm)	Daily Traffic	Type of Backfill	Depth of Backfill (m)	Corrugation Profile	Inside Diameter (mm)	Total Pipe Length (m)	No. Pipe Sections	Specification	Pipe Inspection		
														Date	Frequency	Document
90	Region 5	Storm drain	1994	Back Yard Installation	na	na	gravel	0.15 to 0.9	Smooth interior annular	450	32.1	6	material installation	1993(?)	na	Report
93	Region 1	Culvert	1990	Unpaved Road	na	light	clay (class IV)	0.15 to 0.9	Smooth interior spiral	300 to 900	108	18	none	Sep-96	na	Report
99	Region 4	Culvert Storm drain Cross drain	1987 1989	Asphalt pavement	na	na	gravel sand silt	0.3 to 4.5	Smooth & corrugated interior Spiral & annular	450	32.1	6	material installation	1993(?)	na	Report
100	Region 8	Storm drain	1989	Open space	na	na	Mixed	0.3 to 4.5	Smooth interior spiral	900	150	25	material installation	Jul-95	annual	Video
101-1	Region 5	Culvert	1996	Asphalt pavement	125 to 150	light	Flash fill (fly ash, sand & water)	3	Smooth interior spiral	900	12	2	none	May-97	twice	none
101-2	Region 5	Storm drain	1996	Back of lot	na	na	Sand	1.5	Smooth interior annular	1200	92.7	16	none	Oct-96	spot checks	none
101-3	Region 5	Storm drain	1993	Asphalt pavement	na	na	Sand	2.1	Smooth interior spiral	750	37.8	7	none	May-93	sport check	none
101-4	Region 5	Culvert	1996	Asphalt pavement	100 to 125	light	Flash fill (fly ash, sand & water)	3	Smooth interior annular	600	12	2	none	May-97	twice	none
102-1	Canada	Cross drain	1989	Paved Roadway	na	light	na	7.5 to 9	Corrugated interior spiral	900	60	10	none	Oct-97	1	Reports
102-2	Canada	Cross drain	1985	Unpaved Roadway	na	light	na	0.1	Corrugated interior spiral	150	4.5	0.75	none	Oct-97	1	Reports
102-3	Canada	Culvert	1985	Driveway	na	light	na	0.15	Corrugated interior spiral	450	12	2	none	Oct-97	1	Reports
103-1	Region 10	Cross drain		Unpaved Roadway	na	light	Local soil	0.9	Smooth interior spiral	750	18	3	none	Feb-98	1	Report
103-2	Region 10	Cross drain	1996	Unpaved Roadway	na	light	Local soil	0.6 to 1.2	Smooth interior honeycomb	1200	24	4	none	Feb-98	1	Report

Note: na = nonavailable (i.e., information was not provided)

Table B-2(II) - Response of Questionnaire 2 (Part II)

(Questionnaire No. 2: Responses for Information on Performance of Specific Installation with Corrugated HDPE Pipe)

No.	Assessment of Pipe System's Condition															Accessibility for Inspection	Future Inspection	Permission
	Deflection				Buckling			Splitting or Cracking						Joint				
	No. of Reading	Location	Vertical Diameter (mm)	Horizontal Diameter (mm)	Location	Position in Pipe	Description	No. of Crack	Crack Length (mm)	Locations	Particular Section	Types of Crack	Description	Description				
15	Yes				Yes			Yes						separation		yes	none	yes
	10	vary	575	600	liner	lower half of the pipe	increases with depth of fill	many	vary	many in unlined pipes	at joints in unlined pipe	circumferential	na					
18	5% mandrel didn't fit the pipe	na	na	na	na	na	pipe was crushed in traffic wheel path	na	na	where buckling occurred	na	circumferential	cracking associated with other problem	offsetting buckling		no	no	na
																(All detected problems were removed and replaced at time of construction)		
26	None				portion inside	one side	liner buckled	na	na	headwalls	na	circumferential	na	None		yes	no	Possible
27	Yes				Yes			Yes						None		yes (low tide)	no	yes
28-1	minor				None			1	12.5	na	end near to manhole	circumferential	na	problem with (manhole)		yes	no	yes
28-2	11	first Section	525	650	small buckling			None (tear failure)						problem with (manhole)		yes	no	yes
29	None				None			None						Yes due to construction or settlement		na	na	yes
30	5	first six pipe sections	725	765	None			5	125 to 500	north end of pipe (lower half of the pipe)	first six pipe sections	circumferential	Splits near flow line, random cracks throughout the pipe	na		yes	yes	yes
32	na	top to bottom	100 to 125	100 to 125	None			None						6 joints separated		no	no	yes
34	na	buckled	300	600	west toward headwall	na	na	1	300	west toward headwall	top	circumferential	na	none		no	yes	yes
36	3	west	750	900	west	12 o'clock	construction equipment damage	None						separated at bands		no	no	no
37	visual examination	Entire length deflected	na	na	na	9 o'clock	small buckling	na	na	na	na	circumferential	liner appeared to be split from pipe wall	gravel backfill through joints		yes	no	na
43-1	9	every 3 m through pipe	745	760	None			None						small separations at some joints		no	no	yes
43-2	2	3.9 & 5.4 m from west end	530	628	None			None						small separations at some joints		no	no	yes
43-3	None				None			None						small separations at some joints		no	no	yes
43-4	4	1 to 3 Joints	825	1000	localized buckling at the joints			3	550 to 575	Joints	first 3 pipe sections	circumferential	shear displacement between pipes	none		yes	no	yes
43-5	5	first section of the pipe	925	900	None			4	275 to 925	invert and crown	first section	circumferential	na	none		yes	no	yes

Note: na= non-available (i.e., information was not provided)

Table B-2(II) - Continue

No.	Assessment of Pipe System's Condition														Accessibility for Inspection	Future Inspection	Permission
	Deflection				Buckling			Splitting or Cracking						Joint			
	No. of Reading	Location	Vertical Diameter (mm)	Horizontal Diameter (mm)	Location	Position in Pipe	Description	No. of Crack	Crack Length (mm)	Locations	Particular Section	Types of Crack	Description	Description			
43-6	7	first 7 sections	875	1162.5	buckling at spring line			7	525 to 650	invert and crown	first 7 sections	circumferential & longitudinal	na	none	yes	no	yes
65	na	na	200 to 250	na	many along pipes	na	vertical and horizontal	None						None	no	yes	yes
69	None				portion inside	one side	liner buckled	umerous	18	side wall	many	circumferential & longitudinal	na	pullouts	yes	no	don't know
71	4 length at 10:30 - 4:30 is 975 mm length at 7:30 - 1:30 is 825 mm	na	800	950	12	at 5 and 10 o'clock positions	na	43	75 to 3650	18 at crown 24 at invert 1 full circum-ferential	no	circumferential	na	None	yes	no	don't know
72-1	none	south verticle band	na	na	None			1	na	1.5 m in from outlet	outlet	circumferential & longitudinal	crest	None	na	no	yes
72-2	None				None			1	6000	west side of the pipe	single location	longitudinal	valley and crest	None	yes	no	yes
72-3	4	south	943.5	1066.25	South	Springline at 3 & 9 o'clock	double hinged crush deflection	many	na	na	section 19 to 24	circum-ferential & longitudinal	na	None	yes	yes	yes
72-4	na	0.3 length	50 mm deflection		None			na	na	1.2 m from outl	near outlet	circum-ferential & longitudinal	lost 1.2 m of pipe poor joint & cracks	None	yes	no	yes
72-5	1	0.6 m from outlet	25 mm deflection		None			1	na	top of pipe 0.6 m from outlet	na	circum-ferential	crest of corrugation	None	yes	no	yes
72-6	na	pavement edge	50 mm deflection		None			na	na	na	na	longitudinal	pipe crushed at inlet	None	yes	no	yes
72-7	1	1.5 m from outlet	62.5 mm deflection		None			1	na	1.5 to 1.8 m from outlet	na	circum-ferential	valley of corrugation	None	yes	no	yes
72-8	1	Behind ret. wall at outlet	37.5 mm deflection		None			>1	na	na	na	circum-ferential & longitudinal	cracks appear brittle	None	yes	no	yes
72-9	1	na	50 mm deflection		None			>1	na	1.5 m from outlet	na	circum-ferential	appears slip at outlet	None	yes	no	yes
72-10	na	na	na		None			>1	na	na	na	circum-ferential & longitudinal	top cracked bottom heaved up	None	yes	no	yes
72-11	1	under roadway	87.5 mm deflection		None			>1	na	5 m from inlet	na	circum-ferential & longitudinal	vehicle impact & mower damage at pipe ends	None	yes	no	yes
72-12	none	4.5 m from outlet	na		15' to 20' from outlet	at 3 & 9 o'clock	wall crushed	xcessive	na	4.5 to 6 m from outlet	na	circum-ferential & longitudinal	excessive deflection & wall buckling	None	yes	yes	yes
72-13	none	none	none		None			1	na	0.3 m from inlet end	na	na	outlet section split due to settling of HW	None	yes	no	yes
72-14	none	none	none		None			1	na	0.9 m from end of outlet	na	na	lost last 0.6 m of pipe; slip area	None	yes	no	yes

Note: na= non-available (i.e., information was not provided)

Table B-2(II) - Continue

No.	Assessment of Pipe System's Condition														Accessibility for Inspection	Future Inspection	Permission
	Deflection				Buckling			Splitting or Cracking						Joint			
	No. of Reading	Location	Vertical Diameter (mm)	Horizontal Diameter (mm)	Location	Position in Pipe	Description	No. of Crack	Crack Length (mm)	Locations	Particular Section	Types of Crack	Description	Description			
72-15	1	3 in from outlet	na		None			1	na	na	na	na	end section split due to settling of HW	None	yes	no	yes
72-16	outlet end of the pipe				Bottom of pipe flattened			None - Tear at outlet of pipe through retaining wall. Appears the retaining wall slipped or settled						None	yes	no	yes
72-17	up to 50 mm deflection throughout the pipe				None			None						None	yes	no	yes
72-18	25 mm or more deflection at 1.5 m from inlet end.				None			None						None	yes	no	yes
72-19	37.5 mm deflection				None			unable to see						None	yes	no	yes
72-20	Yes				Bottom flattened up at 3 or 4 places;			None						None	yes	no	yes
72-21	Yes				None			None (don't observe cracks; inlet crushed from 1.2 m in)						None	yes	no	yes
72-22	50 mm deflection				None			None (bottom flat in some places; don't observe cracks; material pliable)						None	na	no	yes
73-1	none	N to S	750	750	None			1	na	na	na	na	na	Separating low end joint strips	yes	no	no
73-2	3	Near Manhole	675	800	None			1	100	1.5 m from manhole end	na	circum-ferential	na	Pipes are deflecting at joints	yes	no	yes
74	None				None			>1	na	na	na	circum-ferential	na	na	yes	no	yes
78-1	5	3 m to 15 m inlet	Ave. 100 mm	Ave. 25 m	None			1	112.5	12 m from up stream	na	circum-ferential	growth from 25 to 112.5mm in one year	na	yes	no	yes
78-2	None				None			None						na	yes	no	yes
79	Yes				top	12 o'clock	na	None						na	no	no	no
84	1	na	na	na	None			many	na	north	top	longitudinal	na	Separation	yes	no	yes
85-1	6	na	675	837.5	None			many	175 to 1175	within 6 m	near junction box	circumferential	na	None	no	no	no
85-5	3	every 4.5 m	1325	1575	None			None						None	no	no	no
89	None				1.8 m from inlet	top of the pipe at 12 o' clock	Pipe crushed - lost 1/2 of the end area	5 to 8	300 to 900	same location	na	longitudinal	another hole at location 9 m from inlet	Rough TV camera can't get through	yes	yes	yes

Note: na= non-available (i.e., information was not provided)

Table B-2(II) - Continue

No.	Assessment of Pipe System's Condition														Accessibility for Inspection	Future Inspection	Permission
	Deflection				Buckling			Splitting or Cracking						Joint			
	No. of Reading	Location	Vertical Diameter (mm)	Horizontal Diameter (mm)	Location	Position in Pipe	Description	No. of Crack	Crack Length (mm)	Locations	Particular Section	Types of Crack	Description	Description			
90	Yes				None			None						Tear at one joint	no	yes	yes
93	Yes (10% to 25%)				Yes			22	vary	vary	na	circumferential	vary from crack to crack	misalignment	na		
99	Yes (5% to 10%)				Yes			4	150 to 175	na	na	circumferential	na	separation	yes	possible	yes
100	Yes (5% to 10%)				Yes			Yes (circumferential cracks)						separation	no	yes/6 month	yes
101-1	No				No			Yes (1 circumferential crack)						None	yes	none	yes
101-2	No				No			Yes						None	yes	none	yes
								1	175	near headwall	no	circumferential	na				
101-3	No				Yes			Yes						None	yes	none	yes
								1	125	near inlet end	no	circumferential	na				
101-4	Yes				No			Yes						None	yes	none	yes
								6	50 to 600	North to pipe end	no	circumferential	na				
102-1	Yes from outlet - 3rd segment vary from 33% to 17% from inlet - 1st segment 17%				No			No						None	yes	none	yes
102-2	No				No			No						None	yes	none	yes
102-3	Yes The vertical deflection no more than 10%				No			No						None	yes	none	yes
103-1	1	first joint	750	750	No			1	25 to 1750	crown	second pipe section	circumferential	na	None	yes	none	yes
103-2	4	first four sections	1100	1225	buckling in sections 3 and 4			1	1425	crown	second pipe section	circumferential & longitudinal	longitudinal crack changed to circumferential	None	yes	none	yes

Note: na= non-available (i.e., information was not provided)

APPENDIX D

MATERIAL PROPERTY TESTING PROCEDURE AND RESULTS

D-1. DENSITY AND CARBON BLACK CONTENT

Density

The density test was performed according to the density gradient method, ASTM D1505. Three replicates were tested and the average reported. One specimen was taken from each of the three 1.8 mm thick plaques. For the pipe wall material, three specimens were taken from different locations of the liner and crest. The actual resin density of samples containing carbon black was calculated based on the average amount of carbon black in the material as measured by ASTM D4218. Table D-1.1 shows the individual test data, the average value, and the corresponding standard deviation of fourteen commercially new pipes. Table D-1.2 shows the test data of nineteen retrieved field pipe samples. The majority of the standard deviation values for each of the three replicates is below the ASTM standard listed value of 0.0012 g/cc.

Carbon Black Content

The amount of carbon black in pipe materials was determined using the ASTM D4218 test procedure. A known mass, approximately 1 ± 0.001 g, of pipe material was placed in an aluminum container. The aluminum container with sample was then placed in a muffle furnace set to a temperature of 600°C. After 3 minutes, the aluminum container was removed from the furnace and placed in a desiccator for cooling. The remaining material, i.e., carbon black, in the container was determined via mass balance. Three replicates were tested for each material. The average values and standard deviation values are listed along with the density in Tables D-1.1 and D-1.2 for both commercially new pipes and retrieved field pipes, respectively. The majority of the standard deviation values is below the ASTM standard listed value, 0.03%. Five samples have a higher standard deviation value, which may have been caused by the variation in the carbon black distribution in the pipe.

Table D-1.1 - Density result via ASTM D1505 for commercially new pipe samples

Sample Code	Type of Material	Test 1 (g/cc)	Test 2 (g/cc)	Test 3 (g/cc)	Average Density (g/cc)	Standard Deviation	Carbon Black (%)	Calculated Density (g/cc)
1	Plaque from RP	0.9476	0.9481	0.9483	0.9480	0.0004	N/A	0.9480
	Plaque from PP	0.9572	0.9568	0.9567	0.9569	0.0003		0.9483
	Pipe Crest	0.9541	0.9541	0.9550	0.9544	0.0005	1.95	0.9458
	Pipe Liner	0.9537	0.9540	0.9558	0.9545	0.0011	(± 0.03)	0.9459
2	Plaque from PP	0.9680	0.9682	0.9673	0.9678	0.0005		0.9560
	Pipe Crest	0.9615	0.9625	0.9638	0.9626	0.0012	2.69	0.9508
	Pipe Liner	0.9654	0.9666	0.9672	0.9664	0.0009	(± 0.02)	0.9546
3	Plaque from PP	0.9589	0.9585	0.9588	0.9587	0.0002		0.9520
	Pipe Crest	0.9578	0.9572	0.9577	0.9576	0.0003	1.52	0.9509
	Pipe Liner	0.9553	0.955	0.9559	0.9554	0.0005	(± 0.03)	0.9487
4	Plaque from RP	0.9544	0.9542	0.9534	0.9540	0.0005	N/A	0.9540
	Plaque from PP	0.9615	0.9615	0.9613	0.9614	0.0001		0.9521
	Pipe Crest	0.9602	0.9607	0.9601	0.9603	0.0003	2.12	0.9510
	Pipe Liner	0.9565	0.9575	0.9567	0.9569	0.0005	(± 0.08)	0.9476
5	Plaque from PP	0.9580	0.9572	0.9571	0.9574	0.0005		0.9519
	Pipe Crest	0.9548	0.9538	0.953	0.9539	0.0009	1.26	0.9483
	Pipe Liner	0.9539	0.9544	0.9537	0.9540	0.0004	(± 0.15)	0.9485
6	Plaque from PP	0.9621	0.9604	0.9643	0.9623	0.0020		0.9525
	Pipe Crest	0.9574	0.9572	0.9568	0.9571	0.0003	2.22	0.9474
	Pipe Liner	0.9618	0.9606	0.9603	0.9609	0.0008	(± 0.02)	0.9511
7	Plaque from RP	0.9517	0.9487	0.9479	0.9494	0.0020	N/A	0.9494
	Plaque from PP	0.9559	0.9556	0.9559	0.9558	0.0002		0.9512
	Pipe Crest	0.9545	0.9544	0.9556	0.9548	0.0007	1.04	0.9503
	Pipe Liner	0.9509	0.9519	0.9506	0.9511	0.0007	(± 0.02)	0.9466
8	Plaque from RP	0.9515	0.9516	0.9513	0.9515	0.0002	N/A	0.9515
	Plaque from PP	0.9624	0.9626	0.9618	0.9623	0.0004		0.9481
	Pipe Crest	N/A	N/A	N/A	N/A	N/A	3.21	N/A
	Pipe Liner	0.9683	0.9683	0.967	0.9679	0.0008	(± 0.09)	0.9537
9	Plaque from PP	0.9565	0.9561	0.9561	0.9562	0.0002		0.9510
	Pipe Crest	0.9553	0.9554	0.9558	0.9555	0.0003	1.20	0.9502
	Pipe Liner	0.9518	0.9516	0.952	0.9518	0.0002	(± 0.02)	0.9465
10	Plaque from RP	same as #4					N/A	0.9540
	Plaque from PP	0.9638	0.9642	0.9622	0.9634	0.0011		0.9548
	Pipe Crest	0.9642	0.9643	0.9631	0.9639	0.0007	1.96	0.9552
	Pipe Liner	0.9571	0.9557	0.9566	0.9565	0.0007	(± 0.12)	0.9478

Table D-1.1 - Continued

Sample Code	Type of Material	Test 1 (g/cc)	Test 2 (g/cc)	Test 3 (g/cc)	Average Density (g/cc)	Standard Deviation	Carbon Black (%)	Calculated Density (g/cc)
11	Plaque from RP	0.9516	0.9507	0.9500	0.9508	0.0008	N/A	0.9508
	Plaque from PP	0.9551	0.9555	0.9555	0.9554	0.0002	1.00 (± 0.01)	0.9510
	Pipe Crest	0.9527	0.952	0.9519	0.9522	0.0004		0.9478
	Pipe Liner	0.9544	0.9508	0.9538	0.9530	0.0019		0.9486
12	Plaque from PP	0.9558	0.9559	0.9559	0.9559	0.0001	1.48 (± 0.03)	0.9494
	Pipe Crest	0.9525	0.9527	0.9508	0.9520	0.0010		0.9455
	Pipe Liner	0.9515	0.9516	0.9515	0.9515	0.0001		0.9450
13	Plaque from PP	0.9494	0.9499	0.9496	0.9496	0.0003	0.09 (± 0.001)	0.9492
	Pipe Crest	0.9462	0.9465	0.9480	0.9469	0.0010		0.9465
	Pipe Liner	0.9448	0.9458	0.9457	0.9454	0.0006		0.9450
14	Plaque from RP	0.9549	0.9554	0.9554	0.9552	0.0003	N/A	0.9552
	Plaque from PP	0.9618	0.9617	0.9609	0.9615	0.0005	1.8200 (± 0.04)	0.9535

N/A = Non-applicable
RP = Resin Pellets
PP = Pipe Pieces

Table D-1.2 - Density result via ASTM D1505 for retrieved field pipe samples

Site	Type of Material	Test 1 (g/cc)	Test 2 (g/cc)	Test 3 (g/cc)	Average Density (g/cc)	Standard Deviation	Carbon Black (g)	Calculated Density (g/cc)
A	Plaque from pp	0.9723	0.9716	0.9714	0.9718	0.0005	2.43	0.9611
B	Plaque from pp	0.9630	0.9621	0.9607	0.9619	0.0012	2.32	0.9517
D	Plaque from pp	0.9602	0.9605	0.9605	0.9604	0.0002	1.45	0.9540
E	Plaque from pp	0.9630	0.9642	0.9634	0.9635	0.0006	2.15	0.9541
F	Plaque from pp	0.9613	0.9599	0.9609	0.9607	0.0007	1.44	0.9544
G	Plaque from pp	0.9629	0.9628	0.9623	0.9627	0.0003	1.21	0.9573
H	Plaque from pp	0.9557	0.9576	0.9583	0.9572	0.0013	2.02	0.9483
I	Plaque from pp	0.9579	0.9573	0.9569	0.9574	0.0005	0.93	0.9533
J-1	Plaque from pp	0.9651	0.9651	0.9655	0.9652	0.0002	2.20	0.9556
J-2	Plaque from pp	0.9620	0.9621	0.9625	0.9622	0.0003	2.19	0.9526
K	Plaque from pp	0.9610	0.9614	0.9607	0.9610	0.0004	2.45	0.9503
L	Plaque from pp	0.9564	0.9563	0.9563	0.9563	0.0001	1.57	0.9494
N	Plaque from pp	0.9568	0.9567	0.9572	0.9569	0.0003	1.06	0.9522
O	Plaque from pp	0.9618	0.9615	0.9614	0.9616	0.0002	2.15	0.9521
P	Plaque from pp	0.9625	0.9625	0.9621	0.9624	0.0002	2.60	0.9509
R	Plaque from pp	0.9629	0.9625	0.9628	0.9627	0.0002	2.90	0.9500
U	Plaque from pp	0.9602	0.9601	0.9605	0.9603	0.0002	1.54	0.9535
V	Plaque from pp	0.9587	0.9584	0.9584	0.9585	0.0002	1.04	0.9539
W*	Plaque from pp	0.9820	0.9820	0.9820	0.9820	0.0000	6.38	0.9540

* using ASTM D 793 test procedure instead of D 1505 due to the extremely high density value
N/A = Non-applicable

D-2. MELT INDEX

The melt index (MI) test was performed according to ASTM D1238. Two test conditions were evaluated: 190°C at 2.16 kg and 190°C at 21.6 kg. This implies that tests were performed at a temperature of 190°C under compressive load of either 2.16 kg or 21.6 kg. The amount of extruded material under these two loads in a time period of 10 min. was measured. The result is expressed in the unit of g/10 min. The ratio of these two tests (i.e., $MI_{21.6}/MI_{2.16}$) was evaluated and referred to as a flow rate ratio (FRR). Three tests were performed on each material at each test condition. Table D-2.1 shows the average values of two MI tests and the corresponding FRR values of fourteen commercially new pipes. The results of nineteen retrieved field pipes are listed in Table D-2.2. The standard deviation of each three replicates is within the ASTM listed value, which is 0.012 g/10 min. for materials with a 0.4 g/10 min. $MI_{2.16}$ value.

Table D-2.1 - Melt Index results via ASTM D1238 for commercially new pipe samples

Sample	Type of Material	2.16 kg (g/10 min.)	Average Value (Standard Deviation) (g/10 min.)	21.6 kg (g/10 min.)	Average Value (Standard Deviation) (g/10 min.)	FRR (21.6/2.16)
1	Resin Pellet	0.30		19.9		
		0.31	**0.30**	21.2	20.4	68.1
		0.29	(± 0.01)	20.2	(±0.7)	
	Pipe Pieces	0.21		19.5		
		0.20	**0.21**	18.8	19.2	91.4
		0.22	(±0.01)	19.3	(±0.4)	
2	Pipe Pieces	0.52		46.5		
		0.51	**0.51**	47.0	46.4	90.3
		0.52	(±0.01)	45.8	(±0.6)	
3	Pipe Pieces	0.38		31.9		
		0.37	**0.37**	32.8	32.2	86.9
		0.36	(±0.01)	31.8	(±0.6)	
4	Resin Pellet	0.31		29.0		
		0.30	**0.31**	31.0	30.2	97.0
		0.32	(±0.01)	30.5	(±1.0)	
	Pipe Pieces	0.31		31.7		
		0.32	**0.31**	34.6	33.3	106.1
		0.31	(±0.01)	33.7	(±1.5)	
5	Pipe Pieces	0.11		9.0		
		0.08	**0.09**	8.0	8.5	98.0
		0.07	(±0.02)	8.4	(±0.5)	
6	Pipe Pieces	0.42		48.1		
		0.40	**0.40**	43.4	44.5	112.2
		0.37	(±0.03)	42.0	(±3.2)	
7	Resin Pellet	0.35		36.17		
		0.35	**0.35**	36.57	36.3	103.6
		0.35	(±0.00)	36.02	(±0.5)	
	Pipe Pieces	0.36		37.93		
		0.37	**0.36**	38.63	38.2	93.6
		0.36	(±0.00)	38.19	(±0.4)	
8	Resin Pellet	0.05		9.7		
		0.05	**0.05**	9.6	9.6	192.7
		0.05	(±0.00)	9.7	(±0.1)	
	Pipe Pieces	0.04		8.8		
		0.04	**0.04**	8.9	8.9	221.7
		0.04	(±0.00)	8.9	(±0.1)	

Table D-2.1 - Continued

Sample	Type of Material	2.16 kg (g/10 min.)	Average Value (Standard Deviation) (g/10 min.)	21.6 kg (g/10 min.)	Average Value (Standard Deviation) (g/10 min.)	FRR (21.6/2.16)
9	Pipe Pieces	0.26		34.9		
		0.26	**0.26**	34.8	34.8	133.9
		0.26	(±0.00)	34.8	(±0.1)	
10	Resin Pellet	0.31		29.0		
		0.30	**0.31**	31.0	30.2	97.0
		0.32	(±0.01)	30.5	(±1.0)	
	Pipe Pieces	0.40		35.4		
		0.39	**0.39**	36.5	36.0	91.6
		0.39	(±0.01)	36.0	(±0.6)	
11	Resin Pellet	0.30		44.2		
		0.31	**0.31**	43.8	44.1	143.5
		0.31	(±0.00)	44.2	(±0.2)	
	Pipe Pieces	0.27		42.6		
		0.26	**0.26**	41.0	41.6	158.0
		0.26	(±0.01)	41.3	(±0.8)	
12	Pipe Pieces	0.23		20.9		
		0.23	**0.23**	20.5	20.7	89.9
		0.23	(±0.00)	20.6	(±0.2)	
13	Pipe Pieces	0.23		20.6		
		0.23	**0.23**	20.7	20.5	89.3
		0.23	(±0.00)	20.3	(±0.2)	
14	Resin Pellet	0.34		32.6		
		0.35	**0.35**	29.1	31.0	90.0
		0.35	(±0.00)	31.5	(±1.8)	
	Pipe Pieces	0.46		40.2		
		0.46	**0.46**	43.7	42.2	91.8
		0.46	(±0.00)	42.9	(±1.9)	

Table D-2.2 - Melt Index results via ASTM D1238 for retrieved field pipe samples

Site	Type of Material	2.16 kg (g/10 min.)	Average Value (standard Deviation) (g/10 min.)	21.6 kg (g/10 min.)	Average Value (Standard Deviation) (g/10 min.)	FRR (21.6/2.16)
A	Pipe Pieces	0.55	**0.55**	49.3	49.8	90.9
		0.55		49.1		
		0.55		51.0		
B	Pipe Pieces	0.26	**0.27**	40.0	40.1	151.2
		0.27		40.1		
		0.27		40.2		
D	Pipe Pieces	0.21	**0.21**	23.0	23.5	114.0
		0.20		23.8		
		0.21		23.7		
E	Pipe Pieces	0.23	**0.23**	20.1	20.1	87.8
		0.23		19.9		
		0.23		20.1		
F	Pipe Pieces	0.26	**0.26**	25.7	25.4	99.1
		0.26		25.7		
		0.26		24.8		
G	Pipe Pieces	0.36	**0.36**	38.4	35.6	99.4
		0.36		32.7		
		0.36		35.6		
H	Pipe Pieces	0.14	**0.14**	18.3	17.0	119.2
		0.13		16.2		
		0.15		16.5		
I	Pipe Pieces	0.26	**0.26**	32.0	32.0	125.2
		0.26		32.2		
		0.25		31.8		
J-1	Pipe Pieces	0.07	**0.07**	9.8	9.8	145.0
		0.07		9.9		
		0.07		9.8		
J-2	Pipe Pieces	0.36	**0.36**	44.1	44.0	121.6
		0.36		43.9		
		0.36		44.0		
K	Pipe Pieces	0.05	**0.05**	10.0	10.0	211.2
		0.05		9.9		
		0.05		10.0		

Table D-2.2 - Continued						
Site	Type of Material	2.16 Kg	Average value	21.6 Kg	Average value	FRR (21.6/2.16)
		(g/10 min.)	(g/10 min.)	(g/10 min.)	(g/10 min.)	
L	Pipe Pieces	0.04		7.5		
		0.04	**0.04**	7.8	7.7	192.0
		0.04		7.7		
N	Pipe Pieces	0.06		8.2		
		0.07	**0.06**	8.3	8.2	128.2
		0.06		8.1		
O	Pipe Pieces	0.30		35.2		
		0.30	**0.30**	35.2	35.2	117.9
		0.30		35.3		
P	Pipe Pieces	0.09		15.8		
		0.09	**0.09**	15.4	15.6	171.7
		0.09		15.5		
R	Pipe Pieces	0.06		12.0		
		0.06	**0.06**	12.0	12.0	200.6
		0.06		12.1		
U	Pipe Pieces	0.42		48.2		
		0.42	**0.42**	48.1	48.2	114.7
		0.42		48.2		
V	Pipe Pieces	0.05		8.8		
		0.05	**0.05**	8.8	8.8	176.0
		0.05		8.8		
W	Pipe Pieces	0.21		23.3		
		0.21	**0.21**	23.5	23.4	111.4
		0.21		23.4		

D-3. FLEXURAL MODULUS

This test was performed according to ASTM D790. Only compression plaques that were made from resin pellets and cut pipe pieces were evaluated. The dimensions of the specimen and the crosshead speed used for the tests were according to ASTM D3350. A 50 mm test span was used. The dimensions of the test specimen are 3.2 mm depth (i.e., thickness) and 12.7 mm width. Five specimens were taken from the 3.2 mm thick plaque. The flexural modulus at 2% strain was measured. The average flexural modulus at 2% strain for commercially new pipes and retrieved field pipes are shown in Tables D-3.1 and D-3.2, respectively.

Table D-3.1 - Flextural modulus via ASTM D790 for commercially new pipe samples

Sample Code	Type of Material	Average Flexural Modulus (Standard Deviation) (MPa)
1	Resin Pellet	922 (± 38)
	Pipe Pieces	998 (± 26)
2	Pipe Pieces	995 (± 11)
3	Pipe Pieces	934 (± 27)
4	Resin Pellet	939 (± 21)
	Pipe Pieces	969 (± 19)
5	Pipe Pieces	954 (± 53)
6	Pipe Pieces	1,037 (± 36)
7	Resin Pellet	833 (± 34)
	Pipe Pieces	868 (± 29)

Sample Code	Type of Material	Average Flexural Modulus (Standard Deviation) (MPa)
8	Resin Pellet	969 (± 37)
	Pipe Pieces	977 (± 25)
9	Pipe Pieces	970 (± 35)
10	Resin Pellet	939 (± 21)
	Pipe Pieces	969 (± 19)
11	Pipe resin	899 (± 16)
	Pipe Pieces	921 (± 22)
12	Resin Pieces	900 (± 24)
13	Pipe Pieces	905 (± 58)
14	Resin Pellet	1,157 (± 59)
	Pipe Pieces	1,123 (± 28)

Table D-3.2 - Flextural modulus via ASTM D790 for retrieved field pipe samples

Site	Pipe Style	Average Flexural Modulus (Standard Deviation) (MPa)
A	Type C- helical	1,259 (± 40)
B	Type C-helical	948 (± 31)
D	Type C - annular	805 (± 14)
E	Type S - honeycomb	na
F	Type S - helical	972 (± 29)
G	Type S - annular	983 (± 30)
H	Type C - helical	927 (± 15)
I	Type S - annular	1,020 (± 47)
J-1	Type S - helical	935 (± 34)
J-2	Type S - annular	817 (± 12)

Site	Pipe Style	Average Flexural Modulus (Standard Deviation) (MPa)
K	Type S - annular	na
L	Type C - helical	646 (± 44)
N	Type C - helical	760 (± 19)
O	Type C - helical	910 (± 53)
P	Type S - annular	na
R	Type S - helical	898 (± 22)
U	Type S-honeycomb	na
V	Type C - helical	na
W	Type S-honeycomb	na

na = not available due to insufficient material

D-4. TENSILE YIELD STRENGTH

The tensile yield stress was evaluated according to ASTM D638-Type IV with a crosshead speed of 50 mm/min. This test was performed on plaques that were made from resin pellets and pipe pieces. Five specimens were taken from three 1.8 mm thick plaques. The yield stress and breaking elongation were recorded from each of the tests. The test data of commercially new pipes and retrieved field pipes are shown in Table D-4.1 and D-4.2, respectively. Within each set of five tests, the variability in yield stresses is much lower than the corresponding breaking elongation due to the possible boundary effects between pipe pieces.

Table D-4.1 - Yield Strength via ASTM D 638 for commercially new pipe samples

Sample Code	Type of Material	Average Yield Strength (Standard Deviation) (MPa)	Average Break Elongation (Standard Deviation) (%)
1	Resin Pellets	23.6 (± 0.4)	1229 (± 312)
	Pipe Pieces	24.0 (± 1.0)	795 (± 278)
2	Pipe Pieces	28.0 (± 0.3)	147 (± 46)
3	Pipe Pieces	28.0 (± 1.7)	492 (± 242)
4	Resin Pellets	26.8 (± 0.3)	2469 (± 314)
	Pipe Pieces	27.6 (± 0.2)	390 (± 108)
5	Pipe Pieces	24.7 (± 0.5)	732 (± 400)
6	Pipe Pieces	25.8 (± 0.5)	353 (± 226)
7	Resin Pellets	26.6 (± 0.9)	806 (± 40)
	Pipe Pieces	26.5 (± 0.6)	523 (± 221)
8	Resin Pellets	24.8 (± 0.3)	1128 (± 227)
	Pipe Pieces	23.4 (± 0.8)	1091 (± 155)
9	Pipe Pieces	28.4 (± 0.3)	394 (± 207)
10	Resin Pellets	26.8 (± 0.3)	2469 (± 314)
	Pipe Pieces	26.2 (± 0.5)	308 (± 123)
11	Resin Pellets	26.8 (± 0.8)	799 (± 173)
	Pipe Pieces	26.9 (± 0.6)	392 (± 96)
12	Pipe Pieces	26.2 (± 0.3)	833 (±70)
13	Pipe Pieces	26.1 (± 0.4)	1160 (±148)
14	Resin Pellets	27.5 (± 0.5)	947 (± 143)
	Pipe Pieces	26.0 (± 0.4)	630 (± 278)

Table D-4.2 - Yield Strength via ASTM D638 for retrieved field pipe samples

Site	Pipe Style	Average Yield Strength (Standard Deviation) (MPa)	Average Break Elongation (Standard Deviation) (%)
A	Type C- helical	44 (± 0.2)	94 (± 29)
B	Type C-helical	26.5 (± 0.7)	345 (± 284)
D	Type C - annular	23.4 (± 0.2)	131 (± 61)
E	Type S - honeycomb	30.5 (± 0.3)	210 (± 128)
F	Type S - helical	28.2 (± 0.4)	721 (± 325)
G	Type S - annular	38.6 (± 0.8)	214 (± 89)
H	Type C - helical	26.2 (± 0.3)	518 (± 281)
I	Type S - annular	26.9 (± 0.6)	899 (± 287)
J-1	Type S - helical	25.8 (± 0.6)	1194 (± 40)
J-2	Type S - annular	30.4 (± 0.2)	108 (± 42)
K	Type S - annular	25.2 (± 0.6)	790 (± 257)
L	Type C - helical	26.6 (± 0.5)	572 (± 239)
N	Type C - helical	28.1 (± 0.2)	687 (± 302)
O	Type C - helical	27.6 (± 0.3)	306 (± 96)
P	Type S - annular	28.5 (± 0.4)	212 (± 147)
R	Type S - helical	25.9 (± 0.2)	516 (± 214)
U	Type S-honeycomb	28.6 (± 0.3)	164 (± 77)
V	Type C - helical	27.1 (± 0.3)	644 (± 398)
W	Type S-honeycomb	30 (± 0.4)	34 (± 7)

D-5. ENVIRONMENTAL STRESS CRACK RESISTANCE

The current test to evaluate the environmental stress crack resistance (ESCR) of polyethylene pipe materials is ASTM D1693. The defined test condition is condition B, using 10% Igepal at 50°C. The test was performed on plaques that were made from resin pellets and pipe pieces. Ten specimens were taken from the three 1.8 mm plaques. A 0.3 mm deep notch was introduced on the surface of the specimens. The notched specimens were then bent in a 180° arc and placed within the flanges of a small channel. The entire assembly with 10 specimens was immersed in a bath containing 10% Igepal solution at 50°C. The cracking of the 10 test specimens was monitored frequently and the number of cracked specimens were identified. All tests were ceased after 24 hours as defined in the standard. Tables D-5.1 and D-5.2 show the number of cracked specimens and the total duration of testing time for commercially new pipes and retrieved field pipes, respectively.

Table D-5.1 - ESCR via ASTM D1693 for commercially new pipe samples

Sample Code	Type of Material	Result number of cracked specimens after 24 hours
1	Resin Pellets	none
	Pipe Pieces	none
2	Pipe Pieces	10 (all failed after 14 hours)
3	Pipe Pieces	10 (all failed after 19 hours)
4	Resin Pellets	10 (50% failed after 13 hours)
	Pipe Pieces	10 (50% failed after 12 hours)
5	Pipe Pieces	none
6	Pipe Pieces	none
7	Resin Pellets	10 (all failed after 20 hours)
	Pipe Pieces	10 (all failed after 16 hours)
8	Resin Pellets	none
	Pipe Pieces	none
9	Pipe Pieces	10 (all failed after 21 hours)
10	Resin Pellets	10 (50% failed after 13 hours)
	Pipe Pieces	10 (50% failed after 15 hours)
11	Resin Pellets	10 (all failed after 20 hours)
	Pipe Pieces	10 (all failed after 20 hours)
12	Pipe Pieces	none
13	Pipe Pieces	none
14	Resin Pellets	10 (50% failed after 8 hours)
	Pipe Pieces	10 (50% failed after 10 hours)

Table D-5.2 - ESCR via ASTM D1693 for retrieved field pipe samples

Site	Type of Material	Result no. of cracked specimens after 24 hours
A	Pipe Pieces	10 (All failed after 15 hours)
B	Pipe Pieces	10 (All failed after 13 hours)
D	Pipe Pieces	10 (All failed after 10 hours)
E	Pipe Pieces	10 (All failed after 13 hours)
F	Pipe Pieces	10 (8 failed after 13 hours)
G	Pipe Pieces	10 (All failed after 15 hours)
H	Pipe Pieces	None
I	Pipe Pieces	10 (All failed after 16 hours)
J-1	Pipe Pieces	None
J-2	Pipe Pieces	10 (All failed after 18 hours)
K	Pipe Pieces	None
L	Pipe Pieces	None
N	Pipe Pieces	None
O	Pipe Pieces	10 (All failed after 16 hours)
P	Pipe Pieces	None
R	Pipe Pieces	None
U	Pipe Pieces	10 (All failed after 17 hours)
V	Pipe Pieces	None
W	Pipe Pieces	10 (All failed after 12 hours)

D-6. OXIDATIVE INDUCTION TIME

The oxidative OIT test was performed according to ASTM D3895 using differential scanning calorimetry (DSC). One specimen was taken from each of the three 1.8 mm thick plaques. In addition, specimens were taken directly from two locations of the pipe wall, crest and liner, to determine the effect of compression molding on the OIT value. A test specimen weighing approximately 5 ± 0.01 mg was placed in the DSC device. The specimen was heated from room temperature to 200°C under a nitrogen atmosphere at a rate of 20°C/min. Once the temperature reached 200°C, oxygen was introduced into the device. The specimen was then held at 200°C until an exothermic reaction, i.e., oxidation of the polymer, was detected. The OIT is equal to the time length from the introduction of oxygen to the onset of the exothermic reaction. The test data and standard deviation of commercially new pipes and retrieved field pipes are shown in Tables D-6.1 and D-6.2.

Table D-6.1 - Oxidative Induction Time (OIT) for commercially new pipe materials

Sample Code	Type of Material	Specimen 1 (min.)	Specimen 2 (min.)	Specimen 3 (min.)	Average OIT (min.)	Standard Deviation (min.)
1	Plaque from RP	23	22	23	23	0.6
	Plaque from PP	28	28	27	28	0.6
	Pipe Crest	27	27	25	26	1.2
	Pipe Liner	27	28	28	28	0.6
2	Plaque from PP	7.6	4.1	5.2	5.6	1.8
	Pipe Crest	8.6	7.6	6.8	7.7	0.9
	Pipe Liner	7.6	7.2	8.0	7.6	0.4
3	Plaque from PP	4.3	6.2	4.0	4.8	1.3
	Pipe Crest	10	10	11	10	0.6
	Pipe Liner	11	10	9	10	1.0
4	Plaque from PP	2.5	1.8	2.4	2	0.5
	Pipe Crest	2.4	3.1	1.9	2.5	0.6
	Pipe Liner	3.2	3.7	3.9	3.6	0.4
5	Plaque from PP	35	35	37	36	1.2
	Pipe Crest	39	36	36	37	1.7
	Pipe Liner	37	37	37	37	0.0
6	Plaque from PP	9.0	9.2	14	11	2.8
	Pipe Crest	13	13	12	13	0.6
	Pipe Liner	16	19	18	18	1.5
7	Plaque from PP	14	12	11	12	1.5
	Pipe Crest	12	13	15	13	1.5
	Pipe Liner	14	12	14	13	1.2
8	Plaque from RP	42	45	51	46	4.6
	Plaque from PP	42	44	39	42	2.5
	Pipe Crest	43	40	41	41	1.5
	Pipe Liner	43	44	44	44	0.6
9	Plaque from PP	0.9	0.9	0.8	0.9	0.1
10	Plaque from PP	4.3	2	2.6	3.0	1.2
	Pipe Crest	3.6	3.2	3	3.3	0.3
	Pipe Liner	4.0	5.3	5.1	4.8	0.7
11	Plaque from PP	2.8	2.7	2.6	2.7	0.1
12	Plaque from PP	21	23	23	22	1.2
13	Plaque from PP	21	21	20	20	0.8
14	Plaque from RP	5.6	5.3	4.9	5.3	0.4
	Plaque from PP	7.7	8.3	7.8	7.9	0.3

RP = Resin Pellets

PP = Pipe Pieces

Table D-6.2 - Oxidative Induction Time (OIT) for retrieved field pipe samples

Site	Type of Material	Test 1 (min.)	Test 2 (min.)	Test 3 (min.)	Average OIT (min.)	Standard Deviation
A	Plaque from pp	2.1	1.5	2.5	2.0	0.5
B	Plaque from pp	10.7	11.0	9.8	10.5	0.6
D	Plaque from pp	4.3	3.2	5.3	4.3	1.1
E	Plaque from pp	5.2	3.7	3.9	4.3	0.8
F	Plaque from pp	11.4	7.6	7.5	8.8	2.2
G	Plaque from pp	7.2	11.0	15.0	11.1	3.9
H	Plaque from pp	18.0	17.0	19.0	18.0	1.0
I	Plaque from pp	0.3	0.2	0.2	0.2	0.0
J-1	Plaque from pp	4.8	9.0	8.5	7.4	2.3
J-2	Plaque from pp	6.5	5.8	5.2	5.8	0.6
K	Plaque from pp	15.9	11.8	16.1	14.6	2.4
L	Plaque from pp	9.0	13.0	9.0	10.3	2.3
N	Plaque from pp	12.7	18.9	18.2	16.6	3.4
O	Plaque from pp	7.6	6.2	4.1	6.0	1.8
P	Plaque from pp	0.6	0.5	4.5	1.9	2.3
R	Plaque from pp	6.0	6.0	7.6	6.5	0.9
U	Plaque from pp	0.2	0.7	1.0	0.6	0.4
V	Plaque from pp	18.2	18.8	14.5	17.2	2.3
W	Plaque from pp	13.7	11.4	8.7	11.3	2.5

APPENDIX E

NCTL TEST RESULTS

E-1. Response Curves of P-NCTL Tests for Resin Pellets and Pipe Pieces

E-2. Results of NCTL and P-NCTL Tests of Fourteen Commercially New Pipes

E-1. Response Curves of P-NCTL Tests for

Resin Pellets and Pipe Pieces

E-2. Results of NCTL and P-NCTL Test of Fourteen
Commercially New Pipes

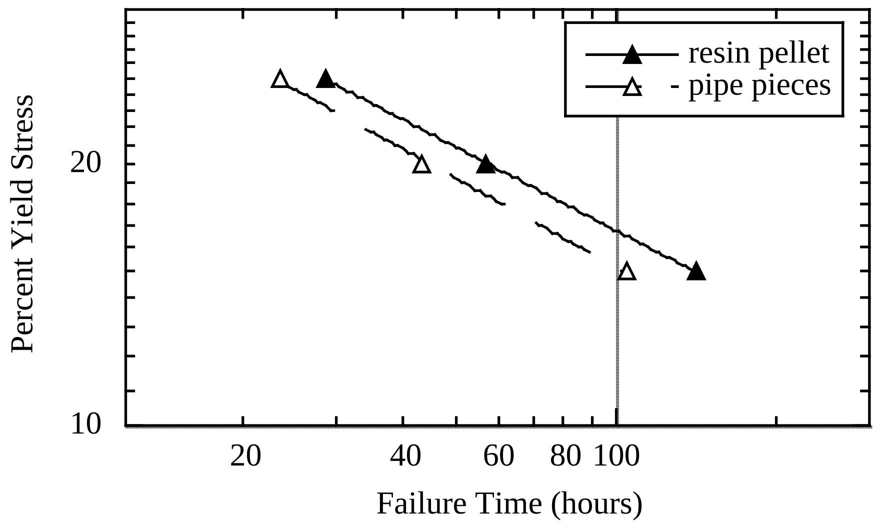


Figure E-1.1 - Response curve of the P-NCTL test for pipe Sample #1.

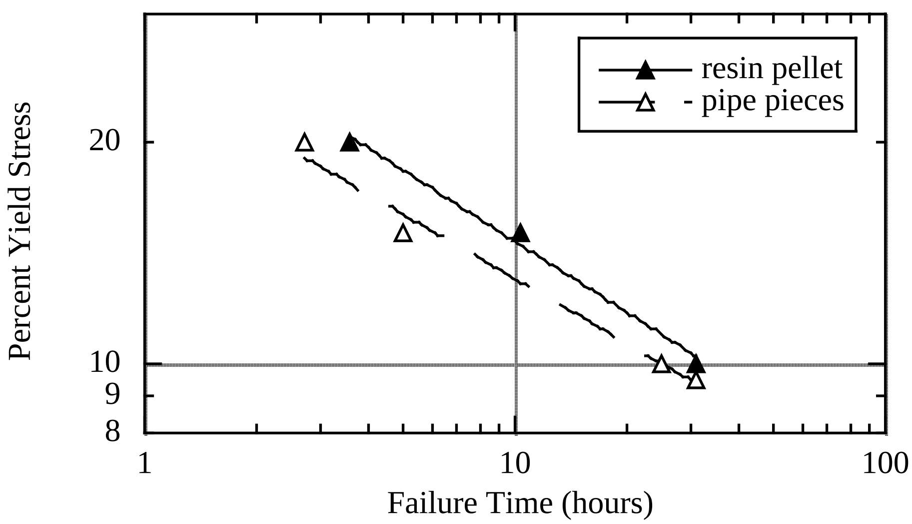


Figure E-1.2 - Response curve of the P-NCTL test for pipe Sample #4.

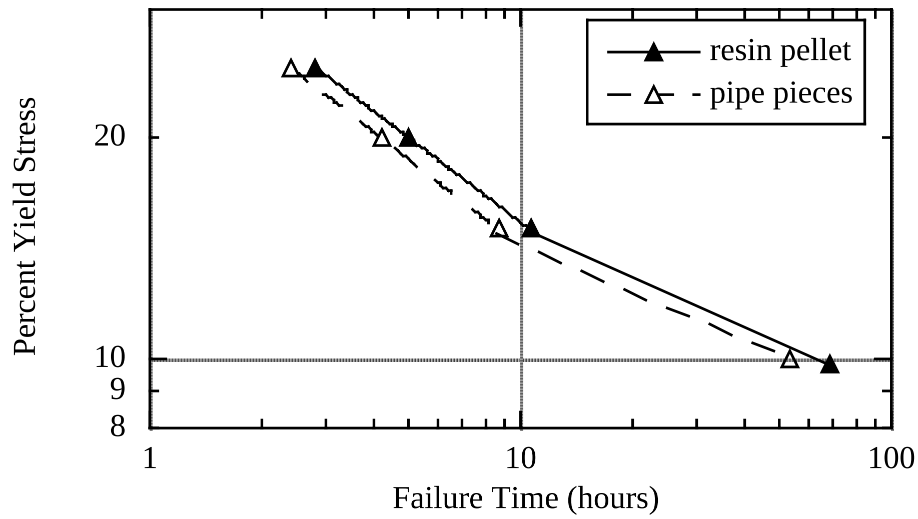


Figure E-1.3 - Response curve of the P-NCTL test for pipe Sample #7

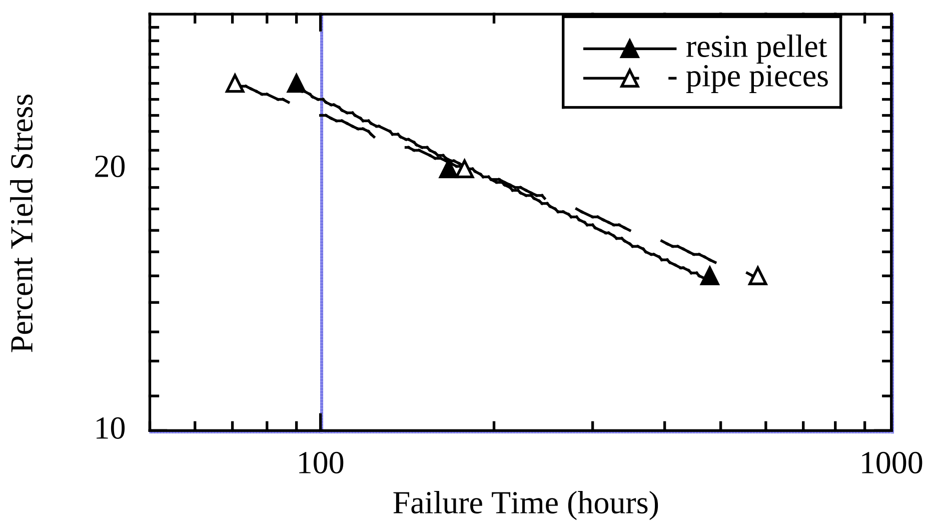


Figure E-1.4 - Response curve of the P-NCTL test for pipe Sample #8

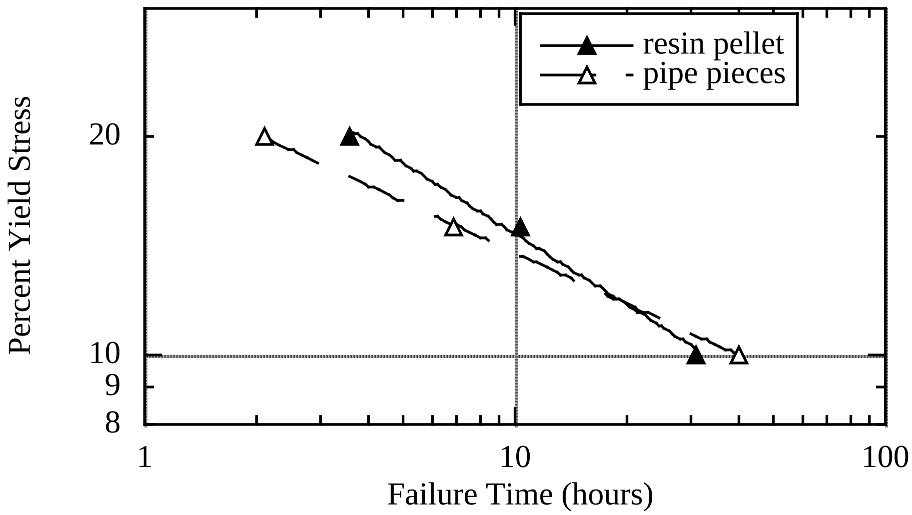


Figure E-1.5 - Response curve of the P-NCTL test for pipe Sample #10

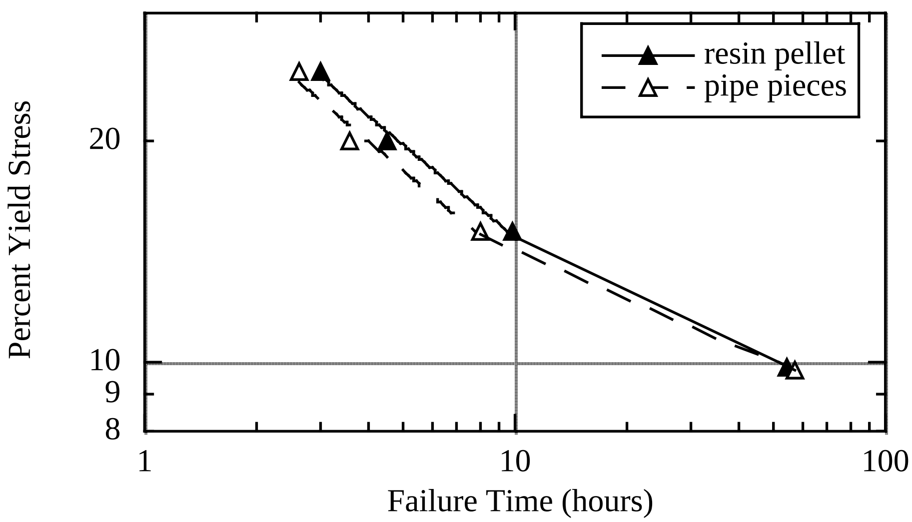


Figure E-1.6 - Response curve of the P-NCTL test for pipe Sample #11

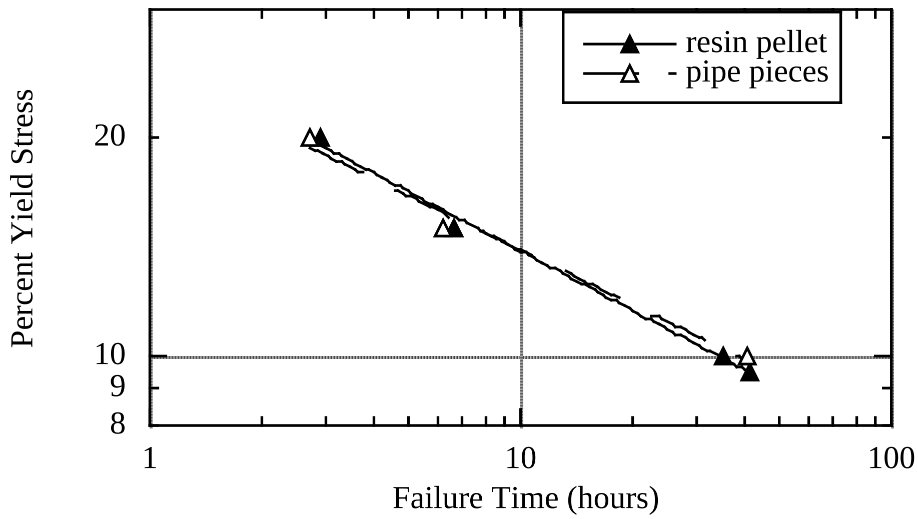


Figure E-1.7 - Response curve of the P-NCTL test for pipe Sample #14

Table E-2.1 - Test Data Obtained from Sample #1

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time (hr.)	Std. Div. of Failure Time (hr.)
Resin Pellet; yield stress = 23.4 MPa (3400 psi)			
50% 11.7 (1700)	0.6 0.6 0.8	0.7	0.12
47.5% 11.1 (1615)	1.1 1.1 1.2	1.1	0.05
45% 10.5 (1530)	4.7 2.6 2.3	3.2	1.3
42.5% 10 (1445)	7.2 7.1 7.6	7.3	0.3
40% 9.4 (1360)	7.9 8.4 8.4	8.2	0.3
37.5% 8.8 (1275)	7.8 7.8 8.1	7.9	0.2
35% 8.2 (1190)	8.6 8.9 8.8	8.8	0.2
32.5% 7.6 (1105)	11.3 12.4 14.6	12.8	1.7
30% 7.0 (1020)	17.9 18.0 17.3	17.7	0.4
25% 5.9 (850)	27.7 28.3 30.9 27.7 27.3	28.4	1
20% 4.7 (680)	51.4 54.0 54.1 62.9 61.5	56.8	5
15% 3.5 (510)	158.1 133.4 140.2 139.6 140.4	142	9

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time (hr.)	Std. Div. of Failure Time (hr.)
Pipe Peices; yield stress = 23.8 MPa (3450 psi)			
25% 5.9 (863)	25.2 22.6 22.3 22.6 24.0	23.3	1.2
20% 4.8 (690)	40.6 46.3 44.5 43.1 42.7	43.4	2.1
15% 3.6 (518)	98.2 117.4 104.2 99.4 105.5	104.9	7.6

Table E-2.2 - Test Data Obtained from Sample #2

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time of the Plaque (hr.)	Std. Div. of Failure Time of the Plaque (hr.)
Pipe Pieces; yield stress = 28 MPa (4060 psi)			
25%	1.0		
	0.9		
7 (1015)	1.0	1.0	0.0
	1.0		
	1.0		
20%	1.9		
	2.0		
5.6 (812)	1.9	1.9	0.1
	1.8		
	1.7		
15%	4.3		
	4.1		
4.2 (609)	3.7	4.2	0.3
	4.5		
	4.2		
10%	19.4		
	17.2		
2.8 (406)	15.5	15.8	2.6
	14.1		
	12.7		

Table E-2.3 - Test Data Obtained from Sample #3

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time of the Plaque (hr.)	Std. Div. of Failure Time of the Plaque (hr.)
Pipe Pieces; yield stress = 28 MPa (4060 psi)			
25% 7 (1015)	4.4 4.0 3.9 3.7 4.7	4.1	0.4
20% 5.6 (812)	6.9 6.4 6.2 6.7 6.4	6.5	0.3
15% 4.2 (609)	13.7 11.8 11.1 13.8 15.3	13.1	1.7
10% 2.8 (406)	85.2 76.1 78.4 85.3 78.5	80.7	4.3

Table E-2.4 - Test Data Obtained from Sample #4

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time of the Plaque (hr.)	Std. Div. of Failure Time of the Plaque (hr.)
Resin Pellet; yield stress = 26.2 MPa (3800 psi)			
20%	4.3		
	4.1		
5.2 (760)	3.2	3.6	0.6
	3.1		
	3.3		
15%	10.7		
	10.6		
3.9 (570)	9.8	10.0	0.7
	10.0		
	9.1		
10%	33.1		
	23.8		
2.6 (380)	36.4	30.2	5.5
	25.0		
	32.8		
Pipe Pieces; yield stress = 27.6 MPa (4000 psi)			
20%	2.6		
	2.8		
5.5 (800)	2.4	2.7	0.3
	2.7		
	3.2		
15%	4.8		
	4.9		
4.1 (600)	5.3	5.0	0.3
	5.4		
	4.6		
10%	31.9		
	22.2		
2.8 (400)	23.7	24.9	5.0
	27.7		
	19.2		

Table E-2.5 - Test Data Obtained from Sample #5

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time of the Plaque (hr.)	Std. Div. of Failure Time of the Plaque (hr.)
Pipe Pieces; yield stress = 24.8 MPa (3600 psi)			
20%	18.4		
	18.8		
5.0 (540)	23.0	22.4	3.7
	25.1		
	26.5		
15%	61.7		
	55.7		
3.7 (540)	49.2	52.6	7.4
	41.9		
	54.4		
10%	354		
	203		
2.6 (380)	265	296.0	61.7
	336		
	322		

Table E-2.6 - Test Data Obtained from Sample #6

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time of the Plaque (hr.)	Std. Div. of Failure Time of the Plaque (hr.)
Pipe Pieces; yield stress = 25.8 MPa (3740 psi)			
20%	8.4		
	7.9		
5.2 (748)	8.1	8.2	0.2
	8.2		
	8.2		
15%	20.2		
	20.1		
3.9 (560)	17.9	18.0	2.1
	16.7		
	15.3		
10%	97.4		
	95.8		
2.6 (380)	103.4	96.7	4.2
	94.7		
	92.1		

Table E-2.7 - Test Data Obtained from Sample #7

Resin Pellet; yield stress = 26.6 MPa (3860 psi)

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time (hr.)	Std. Div. of Failure Time (hr.)
50% 13.3 (1930)	0.24 0.19 0.19	0.2	0.03
47.5% 12.6 (1833)	0.34 0.35 0.39	0.36	0.03
45% 12 (1737)	0.43 0.6 0.5	0.49	0.06
40% 10.6 (1544)	0.68 0.68 0.68	0.68	0.00
35% 9.3 (1351)	0.99 1.06 1.07	1.04	0.04
32.5% 8.7 (1255)	1.25 1.25 1.24	1.25	0.01
30% 8.0 (1158)	1.4 1.4 1.4	1.40	0.00
27.5% 7.3 (1062)	1.8 1.9 1.6	1.77	0.15
25% 6.9 (1003)	2.6 2.9 2.8 2.8 3.0	2.8	0.1
20% 5.5 (802)	4.8 5.0 5.6 5.1 4.7	5.0	0.4
15% 4.2 (602)	11.1 11.1 11.7 9.8 9.4	10.6	1.0
10% 2.7 (380)	70.7 71.8 61.7 78.6 59.1	68.4	7.9

Pipe Peices; yield stress = 26.5 MPa (3840 psi)

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time (hr.)	Std. Div. of Failure Time (hr.)
25% 6.6 (960)	2.4 2.3 2.5 2.3 2.4	2.4	0.1
20% 5.3 (768)	4.4 4.3 4.1 4.2 4.0	4.2	0.2
15% 4.0 (576)	8.4 9.7 9.4 8.1 8.1	8.7	0.8
10% 2.6 (380)	51.8 65.5 58.9 46.4 45.3	53.6	8.6

Table E-2.8 - Test Data Obtained from Sample #8

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time of the Plaque (hr.)	Std. Div. of Failure Time of the Plaque (hr.)
Resin Pellet; yield stress = 24.8 MPa (3600 psi)			
25% 6.2 (900)	102 73.3 69.1 79.6 90.7	82.9	13.4
20% 5.0 (720)	215 161 174 167 122	167.8	33.2
15% 3.7 (540)	489 523 503 431 468	482.8	35.2
Pipe Pieces; yield stress = 23.3 MPa (3380 psi)			
25% 5.8 (845)	69.4 57.4 69.2 64.2 93.4	70.7	13.6
20% 4.7 (676)	145 166 179 194 211	179.0	25.4
15% 3.5 (507)	514 550 595 610 635	580.8	48.5

Table E-2.9 - Test Data Obtained from Sample #9

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time of the Plaque (hr.)	Std. Div. of Failure Time of the Plaque (hr.)
Pipe Pieces; yield stress = 28.5 MPa (4130 psi)			
25%	1.9		
	1.8		
7.1 (1033)	1.7	1.8	0.1
	1.7		
	1.8		
20%	2.9		
	2.8		
5.7 (826)	2.8	2.9	0.1
	2.8		
	3.0		
15%	6.0		
	5.4		
4.3 (620)	6.5	5.7	0.5
	5.4		
	5.3		
10%	32.2		
	28.0		
2.8 (413)	26.1	26.8	3.8
	26.3		
	21.6		

Table E-2.10 - Test Data Obtained from Sample #10

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time of the Plaque (hr.)	Std. Div. of Failure Time of the Plaque (hr.)
Pipe Pieces; yield stress = 26.3 MPa (3810 psi)			
20% 5.3 (762)	1.8 2.4 2.4 2.0 2.0	2.1	0.3
15% 3.9 (572)	6.6 6.1 6.4 7.5 7.2	6.8	0.6
10% 2.6 (380)	39.9 37.8 36.2 48.3 39.1	40.3	4.7

Table E-2.11 - Test Data Obtained from Sample #11

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time of the Plaque (hr.)	Std. Div. of Failure Time of the Plaque (hr.)
Resin Pellet; yield stress = 26.8 MPa (3890 psi)			
25%	3.2		
	2.6		
6.7 (973)	3.2	3.0	0.2
	3.0		
	3.1		
20%	4.9		
	4.1		
5.4 (778)	4.7	4.5	0.3
	4.7		
	4.2		
15%	9.8		
	9.6		
4.0 (584)	9.5	9.9	0.4
	10.3		
	10.4		
9.8%	58.3		
	53.4		
2.6 (380)	53.3	53.9	2.6
	51.1		
	53.6		
Pipe Pieces; yield stress = 26.9 MPa (3900 psi)			
25%	3.6		
	2.3		
6.7 (975)	2.1	2.6	0.7
	2.0		
	3.2		
20%	3.6		
	3.6		
5.4 (780)	3.6	3.6	0.1
	3.5		
	3.7		
15%	8.4		
	7.5		
4.0 (585)	7.4	8.1	0.6
	8.9		
	8.1		
9.7%	62.7		
	56.6		
2.6 (380)	63.8	57.3	5.8
	52.6		
	51.0		

Table E-2.12 - Test Data Obtained from Sample #12

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time of the Plaque (hr.)	Std. Div. of Failure Time of the Plaque (hr.)
Pipe Pieces; yield stress = 26.2 MPa (3800 psi)			
25%	21		
	18.3		
6.6 (950)	19.6	19.0	1.3
	18.2		
	17.7		
20%	29.8		
	31.5		
5.2 (760)	32.4	30.7	1.2
	29.5		
	30.3		
15%	76.1		
	70.0		
3.9 (570)	76.0	72.2	3.5
	69.5		
	69.6		

Table E-2.13 - Test Data Obtained from Sample #13

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time of the Plaque (hr.)	Std. Div. of Failure Time of the Plaque (hr.)
Pipe Pieces; yield stress = 26.1 MPa (3790 psi)			
25%	19.9		
	18.7		
6.5 (948)	19.5	19.1	0.6
	18.3		
	19.2		
20%	34.2		
	34.1		
5.2 (758)	30.2	33.1	1.6
	33.4		
	33.5		
15%	62.2		
	61.2		
3.9 (569)	70.2	64.6	3.7
	66.4		
	63.0		

Table E-2.14 - Test Data Obtained from Sample #14

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time (hr.)	Std. Div. of Failure Time (hr.)
Resin Pellet; yield stress = 27.5 MPa (3990 psi)			
50% 13.8 (1995)	0.03 0.03 0.03	0.03	0.00
45% 13.4 (1796)	0.22 0.23 0.22	0.22	0.01
40% 11 (1596)	0.52 0.54 0.52	0.53	0.01
35% 9.6 (1397)	0.66 0.73 0.67	0.69	0.04
32.5% 8.9 (1297)	0.87 0.87 0.87	0.87	0.00
30% 8.3 (1197)	1.15 0.95 1.08	1.06	0.10
27.5% 7.6 (1098)	1.34 1.44 1.32	1.37	0.06
25% 6.9 (998)	1.83 1.83 1.71	1.79	0.07
20% 5.5 (798)	2.9 3.0 3.1 3.0 2.7	2.9	0.2
15% 4.1 (599)	6.9 7.1 6.6 6.2 6.3	6.6	0.4
10% 2.8 (399)	31 37.9 42.9 35.7 28.4	35.2	5.7

Yield Stress MPa (psi)	Failure Time of the Specimen (hr.)	Average Failure Time (hr.)	Std. Div. of Failure Time (hr.)
Pipe Peices; yield stress = 26.2 MPa (3800 psi)			
20% 5.2 (756)	3.0 2.9 1.9 2.9 2.9	2.7	0.5
15% 3.9 (567)	6.2 5.9 5.6 6.6 6.6	6.2	0.4
10% 2.6 (378)	47.9 42.7 41.1 38.9 33.6	40.8	5.2