LOAD-DURATION BEHAVIOR OF EXTRUDED

WOOD-PLASTIC COMPOSITES

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of CHRISTOPHER WAYNE BRANDT find it satisfactory and recommend that it be accepted.

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Chair

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ABSTRACT

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One of the important characteristics affecting many materials including wood, plastic, and wood-plastic composites is their time-dependent behavior. This behavior can be divided into two separate, yet related, phenomena known as creep and creep-rupture. Creep is the increase in deformation over time while subjected to a sustained load. Creep-rupture, or load-duration behavior, is the eventual failure to sustain a constant load due to increased deformation over time. Both have a considerable effect on wood-plastic composite members and must be accounted for in design. The load-duration, or creep-rupture, behavior of wood and traditional wood composite products has been studied extensively by numerous researchers, and simplified design procedures to account for both effects are in place. However, the load-duration behavior of composite products made out of the combination of wood and plastic is not well understood or documented. Currently, wood-plastic composite products are available on the commercial market, yet no standardized design procedures to account for creep or duration-of-load effects exist.

Given the lack of understanding of the load-duration behavior of wood-plastic composites, a research effort was initiated to investigate the load-duration behavior of various wood-plastic composite formulations and to compare the observed behavior to that of solid sawn lumber.

An exponential damage rate model commonly used for solid wood was found to similarly describe the load-duration effect for wood-plastic composites. Proposed adjustment factors were developed following existing procedures for wood products. It was also found that the current adjustment factors, as found in the 1997 edition of the *National Design Specification for Wood Construction*, can be conservatively applied to wood-plastic composite products, although the adjustment is overly conservative for the materials tested. However, applying adjustment factors based on a short-duration loading was found to be non-conservative.

Rate-of-load effects on flexural properties were also experimentally investigated. It was found that a rate-of-load effect existed for both modulus of rupture and modulus of elasticity over certain ranges of load-rate values. A rate-of-loading corresponding to 0.01 mm/mm/min was found to produce representative material properties that were slightly conservative.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION AND BACKGROUND

INTRODUCTION

Wood structural elements have been used in marine docking and fendering systems for many years. The elastic properties and energy dissipating characteristics of wood make it ideal for use as part of the vessel berthing system in docking structures. Traditionally, preservative treatments have been applied to prolong the life of the wood components in these systems. However, repair, replacement, and disposal of treated wood can be costly. Factor in a decreased service life due to degradation by marine boring organisms, and the opportunity, or need, to introduce new materials to replace wood in these applications becomes quite apparent. The United States Navy has initiated a research effort to develop a suitable replacement for wood structural elements in their docking and fendering systems. Washington State University's Wood Materials and Engineering Laboratory (WMEL) has been contracted by the Office for Naval Research (ONR) to investigate the use of wood-plastic composite (WPC) lumber as a replacement product. WPC elements have an advantage over timber elements due to their ability to resist degradation from marine boring organisms and other environmental factors that significantly reduce the life span of timber components. Additionally, wood-plastic composites can be produced in hollow closed-cell sections allowing the most efficient use of raw materials.

The wood-plastic composite research being conducted at Washington State University's WMEL has been divided into four specific areas of focus: materials development, structural analysis and design, recycling, and demonstration. The information presented in this thesis is one of the many components included within the structural analysis and design effort. The objectives of the structural analysis and design element of the research project are to provide estimates for structural demands, establish design criteria, evaluate component performance through testing, and facilitate the implementation of partial and complete replacement of timber members in waterfront systems.

One of the important characteristics affecting many materials including wood, plastic, and wood-plastic composite products is their time-dependent behavior. This behavior can be divided into two separate, yet related, phenomena known as creep and creep-rupture. Creep is the increase in deformation over time while subjected to a sustained load. Creep-rupture, or load-duration behavior, is the eventual failure to continue sustaining a constant load due to increased deformation over time (creep). Both have a significant effect on WPC product performance and are important issues to consider in load-bearing applications (Sain et al., 2000). However, from a design standpoint, the creep-rupture behavior of a material is of particular interest due to collapse and life-safety implications.

Wood has been characterized as a viscoelastic material governed by creep-rupture behavior (Fridley, 1992a, 1992b), meaning that once loaded, an initial elastic deflection occurs followed by further deflection over time while under constant load that ultimately results in failure. Thermoplastics are also viscoelastic materials (Pomeroy 1978). The load-duration behavior differs from that of wood in that there is no pronounced secondary, or constant region of the displacement-time curve. Instead, an initial displacement occurs followed immediately by creep at a rapid rate that decreases with time until failure (Findley et al., 1976). The load-duration behavior of composite products made out of the combination of wood and plastic is not well understood or documented. Currently, wood-plastic composite products are available on the commercial market, yet no standardized design procedures to account for creep or duration-of-load effects exist.

The research, analysis, and conclusions contained within this thesis focus on the evaluation of the load-duration behavior of near full-sized wood-plastic composite structural products, the effects of load rate on flexural properties, and the development of design procedures to account for load-duration effects.

BACKGROUND

The creep and creep-rupture, or load-duration, behavior of wood and wood composite products has been studied extensively by numerous researchers. Several comprehensive reviews of load-duration research and damage modeling for wood and wood products exist, (Karacabeyli, 1988; Fridley, 1992b, 1995; Nelson, 2000) thus only research pertinent to this experimental study will be discussed.

Wood (1951) conducted one of the earliest and most influential studies on the load-duration behavior of wood. Time-to-failure data was collected for small clear specimens of Douglas-fir subjected to constant center span loads ranging from 60 to 95 percent of the short term strength observed in static tests of matched samples. A hyperbolic model was then fit to the time-to-failure data assuming a stress threshold below which the specimen would not fail. This model (Equation 1-1), better known as the "Madison curve," has the following form:

$$s = \frac{1.084}{t_f^{\,0.04635}} + 0.183 \qquad (1\text{-}1)$$

where σ is the ratio of applied stress to the static test strength, and t_f is the time-to-failure in seconds. The Madison curve, as defined above, is the basis for the load-duration adjustment factors defined in the *National Design Specification for Wood Construction* (AF&PA 1997).

Barrett and Foschi (1978) developed two damage accumulation models based on the data collected by Wood (1951). The first model (Equations 1-2a and 1-2b) is capable of modeling creep-rupture data of a linear form, which they found to adequately represent the vast majority of creep-rupture data for wood. It can be written as follows:

$$\frac{da}{dt} = A(s - s_o)^B a^C \qquad \text{if } s > s_{\text{o}} \tag{1-2a}$$

$$\frac{da}{dt} = 0 \qquad \text{if } s \leq s_{\text{o}} \tag{1-2b}$$

where α is a state variable representing damage ranging from zero, meaning no damage is present, to one, corresponding to failure; dα/dt is the rate of damage accumulation with respect to time; σ is the ratio of applied stress to static test strength; σ_o is a stress threshold below which no damage occurs, and A, B, and C are model constants determined from test data.

The second model (Equations 1-3a and 1-3b) is able to model creep-rupture data of a bilinear form, and was found to provide a better fit to the constant load data of small clear specimens. It is similar to the first model and takes the following form:

$$\frac{da}{dt} = A(s - s_o)^B + Ca \qquad \text{if } s > s_{\text{o}} \tag{1-3a}$$

$$\frac{da}{dt} = 0 \qquad \text{if } s \leq s_{\text{o}} \tag{1-3b}$$

where all parameters are as defined previously.

Foschi and Barrett (1982) later applied their second model to data collected from a one-year load-duration study of visually graded No. 2 and better 2 by 6 Western Hemlock. They were able to conclude that full-sized lumber does, in fact, behave differently than small clear specimens, and that the second model (Equations 1-3a, 1-3b) accurately predicted the load-duration behavior observed for full-sized lumber.

At the same time Barrett and Foschi were developing their damage models, Gerhards (1977, 1979) proposed an exponential cumulative damage approach to modeling load-duration behavior. Again, data from tests of small clear specimens was used. The model (Equation 1-4), which evaluates the amount of damage accumulated using an exponential decay format, commonly referred to as an exponential damage rate model, or EDRM, is given below:

$$\frac{da}{dt} = \exp(-A + Bs) \qquad (1\text{-}4)$$

where all parameters are as defined previously. Further work by Gerhards and Link (1987) included calibrating the EDRM to duration-of-load data from tests of Douglas-fir 2 by 4s, proving that the model applied to not only small clear specimens, but to full-sized lumber as well.

Building upon the second Barrett and Foschi model, yet taking a somewhat different approach, Foschi and Yao (1986) proposed a more complicated damage accumulation model (Equation 1-5). Unlike all of the previously developed models, the Foschi and Yao model is a function of the applied stress as opposed to a function of the applied stress ratio. Their model can be expressed as:

$$\frac{da}{dt} = A(t - t_o)^B + Ca(t - t_o)^D \qquad (1\text{-}5)$$

where τ is the applied stress, τ_o is a stress threshold, D is an additional model constant determined from test data, and all other model parameters are as defined previously. Foschi and Yao concluded that their model provided a more accurate description of the load-duration behavior of lumber than the second Barrett and Foschi model, however solving for five model constants in a consistent and accurate manner may prove to be troublesome.

Gerhards (1988, 1991) continued investigating load-duration behavior of full-sized lumber and found that the allowable bending stress for lumber seemed to be non-conservative for design loads that really exist for the design duration. Based on the data obtained from previous tests and following the methods used in developing the NDS adjustment factors, Gerhards (1988) used his own load-duration equations to propose modifications to the load-duration adjustment factors used in the design of timber structures. These adjustment factors result in lower design values regardless of the design load duration under consideration. Gerhards also concluded that there was no evidence to support the claim of a stress threshold below which no damage occurred. This discovery was in direct contrast with the models developed previously by Wood (1951), Barrett and Foschi (1978), and Foschi and Yao (1986). Additionally, Gerhards (1991) concluded that shorter duration-of-load effects should be the primary focus for those concerned with designing safe timber structures.

Very little documentation exists detailing research focusing on the load-duration behavior of wood-plastic composites. Sain et al. (2000) acknowledge that due to the nature of the material and its complexity there is no general agreement, strategy, or tactic of how to experimentally measure the creep behavior of these composite materials. Sain et al. (2000) focused on the creep fatigue behavior of engineered wood fiber and plastic compositions. The formulations tested were polyvinyl chloride (PVC), polyethylene (PE), or polypropylene (PP) based and contained a constant 30 percent wood fiber by weight. The effects of including maleated polyethylene or polypropylene as a coupling agent were also investigated. Coupon level flexural creep tests were conducted with stress ratios ranging from 10 to 50 percent. Sain et al. (2000) found that creep behavior was a strong function of the loading condition and temperature. PVC formulations were found to be especially sensitive to temperature changes and PE formulations, coupled or uncoupled, showed very low creep resistance. Coupled PP formulations were found to be more resistant to instantaneous creep than uncoupled formulations, however, the transient creep behavior of both was only marginally better than virgin PP.

Xu et al. (2001) examined the creep behavior of wood-filled polystyrene (PS)/HDPE blends. The formulations consisted of 10% to 40% wood flour melt blended with various ratios of the PS/HDPE blend. Three-point bending creep tests were performed on flat rectangular 2 x 12 x 60 mm bars. They found that the addition of wood flour increased the modulus of elasticity and also tended to decrease the creep speed.

Pooler (2001) examined the creep behavior of a high density polyethylene (HDPE) formulation identical to the HDPE 8 formulation reported on herein. Creep tests at 23 °C on 200 x 25 x 13 mm coupons were performed at stress levels ranging from 30% to 90% of ultimate stress. Pooler found that no damage occurred at or below a stress level of approximately 43% of the ultimate stress obtained from static tests.

Despite the valuable insight provided by Sain et al. (2000), Xu et al. (2001), and Pooler (2001) into the creep behavior of WPC products, uncertainty remains in regards to the load-duration behavior of WPC products. Thus, an experimental research program was initiated to characterize the load-duration behavior of WPC materials.

OBJECTIVES

The overall objective of this research project was to conduct an initial evaluation of the load-duration behavior of selected wood-plastic composite formulations representative of high-wood content formulations. Specific objectives are given below:

(1) Evaluate the load-duration behavior and performance of selected wood-plastic composite products through experimental investigation.

(2) Compare the observed load-duration behavior of WPC formulations with that of solid sawn lumber.

(4) Determine the effect of the rate of load application on selected flexural properties of the WPC formulations.

(5) Propose load-duration adjustment factors and a design methodology to be used in the design of structural wood-plastic composite components.

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CHAPTER TWO

EXPERIMENTAL PROCEDURES

INTRODUCTION

Currently, no approved consensus standards exist detailing the procedures to follow to experimentally determine the flexural load-duration behavior of wood-plastic composites. The same is true for wood and wood-based composites; however, numerous load-duration studies have been performed on these materials. Consequently, an acceptable methodology for load-duration research has evolved and is now considered to be standard practice. The methodology consists of experimentally collecting modulus of elasticity (MOE) data and sorting the specimens into statistically equivalent groups. Once sorted, a mean ultimate bending stress is established with static bending tests. Finally, percentages of that stress are applied to each group as a constant load and displacement is recorded over a specified time interval. Due to the nature of wood-plastic composite (WPC) materials, specifically the low COV for material properties, an alternative approach may be more appropriate. The MOE sort and statistical grouping are not necessary and can be excluded from the experimental procedure. Instead of performing an MOE sort, specimens were randomly assigned to test groups in a manner such that each group contained specimens representative of the entire extrusion run. Otherwise, the procedures followed for load-duration testing of WPCs are identical to the "traditional" procedures followed for wood and wood composites. With the emergence of numerous WPC products, the American Society for Testing and Materials (ASTM) committee D-7 has begun to develop a standardized set of procedures and performance criteria for evaluating load-duration behavior of wood and wood-based products. The standard was in the early draft stages at the time this research was conducted, but a concerted effort was made to keep abreast of its development and to adhere to the procedures outlined in it when possible.

MATERIALS

Four wood-plastic composite formulations were selected for evaluation. The first formulation was produced with polyvinyl chloride (PVC) and the remaining three were produced with high density polyethylene (HDPE). The HDPE 8 formulation contained the following processing aides: 2% zinc stearate (Ferro Chemicals Synpro DLG-20B) and 1% EBS wax (GE Specialty). The third HDPE formulation contained an ethylene-maleic anhydride polymer, MAPE, which is a commercially available coupling agent added to strengthen the bond at the interface between the polyethylene and wood fibers. Table 2-1 lists the material composition of each formulation and gives the percentage used by weight.

Table 2-1: *Formulation Materials and Percentages*

Formulation	% Flour	Wood Flour Type	% Plastic	Plastic Type	Additives
PVC	50	Ponderosa Pine (AWF #4020)	50	PVC Compound (Georgia Gulf) (3014 nat 00)	None
HDPE 8	58	Maple (AWF #4010)	31	HDPE (Equistar) (LB 0100 00)	8% Ceramic Talc (Suzqrite) 3% Processing Aides
HDPE 67.5	67.5	Maple (AWF #4010)	32.5	HDPE (Equistar) (LB 0100 00)	None
HDPE 67.5 w/ MAPE	67.5	Maple (AWF #4010)	30.95	HDPE (Equistar) (LB 0100 00)	1.55% MAPE (AlliedSignal) (575A1)

All materials were dry blended in a 1.2-m (4-ft) diameter drum mixer in 20-kg (44-lb) batches. The dry mixture was then loaded into the hopper of a conical counter-rotating twin screw extruder (Cincinnati-Milacron E55) and a two-box cross section was extruded using a stranding die (Laver, 1996) and cut into 2.44-m (8-ft) lengths. Process temperatures are provided in Table 2-2.

Table 2-2: *Extrusion Process Temperatures*

Formulation	Process Temperature (^{o}C)				
	Barrel	Screw	Die Zone 1	Die Zone 2	Die Zone 3
PVC	168	140	174	174	160
HDPE 8	163	163	171	171	171
HDPE 67.5	163	163	163	171	143
HDPE 67.5 w/ MAPE	163	163	163	171	143

Figure 2-1 shows the two-box cross section and Table 2-3 gives the nominal section dimensions and selected properties.

Figure 2-1: *Two-Box Cross Section*

Table 2-3: *Nominal Two-Box Section Dimensions and Properties*

Property	Value
Depth	89 mm (3.5 in.)
Width	36 mm (1.40 in.)
Wall Thickness	5 mm (0.20 in.)
Cross-Sectional Area	1290 mm^2 (2.00 $in.^2$)
Moment of Inertia (Strong Axis)	1.05×10^6 mm^4 (2.52 $in.^4$)

STATIC BENDING TESTS

Static bending tests were necessary to establish a mean short-term flexural strength for the material. This mean short-term flexural strength, or mean ultimate bending stress, is the basis for the stresses applied in the load-duration portion of the experiment.

Twenty-eight specimens from each formulation were weighed to the nearest milligram (2.2×10^{-6} lb) on a digital scale and cross-sectional dimensions were measured to the nearest 0.0254 mm (0.001 in.) with digital calipers. Procedures outlined by Haiar (2000) for determining strong-axis modulus of rupture (MOR) for structural wood-plastic composite beams were followed. The test method specifies that ASTM D198 (1998), a standard test method for determining properties of structural lumber, be followed with two exceptions: load rate and span length. Haiar recommended that the load rate be calculated according to ASTM D790 (1997), a standard test method for determining flexural properties of unreinforced and reinforced plastics. The standard specifies that the load be applied such that the rate of strain in the outer fiber is 0.01 mm/mm/min. (0.01 in./in./min.). Based on nominal section dimensions, this corresponded to a load rate of 62.5 mm/min. (2.46 in./min.). Haiar (2000) recommended that the ratio of support span length to radius of gyration be used to determine the test span; however, a span consistent with that of the load-duration frames, 1.83 m (6 ft), was used. Similarly, the load was applied at third points, or 610 mm (24 in.) from the end reactions to be consistent with the load-duration frames (see subsequent discussion in this chapter). Lateral bracing was provided along the span to ensure that lateral-torsional buckling effects were negligible.

Each specimen was subjected to a ramp load applied by a computer controlled hydraulic actuator until failure occurred. A spreader beam was used to evenly distribute the single point load of the actuator into the two point loads applied to the specimen. Center span displacement was measured using a linear position transducer (UniMeasure LX-PA 10) accurate to +/- 1.27 mm (0.05 in.). A computerized data acquisition system recorded load-displacement data, maximum load, and time-to-failure for each specimen. A schematic of the static bending test setup can be seen in Figure 2-2.

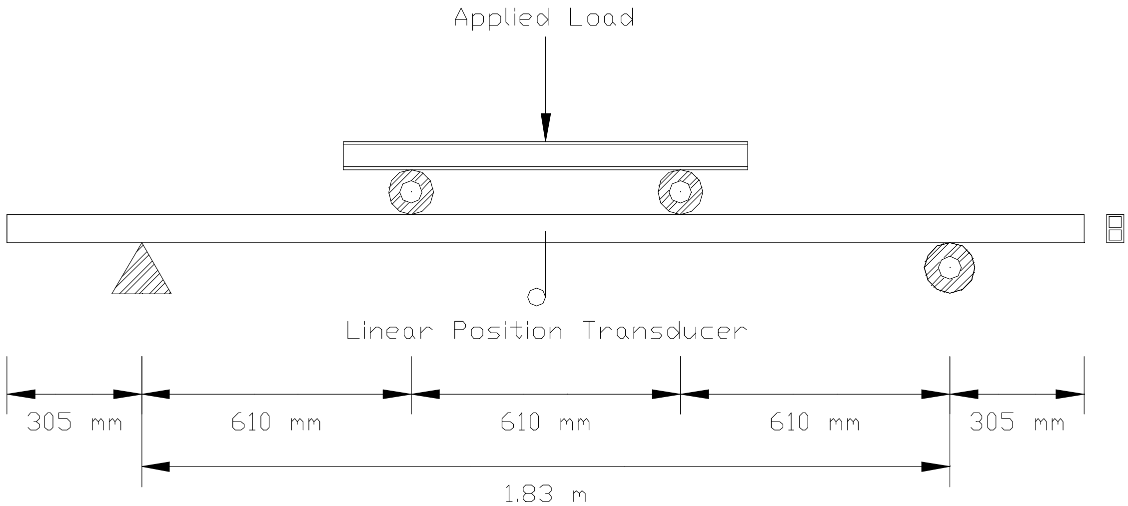

Figure 2-2: *Schematic of Static Test Setup*

DETERMINATION OF LOADS

Cross-sectional dimensions and maximum load data from static bending tests were used to calculate the MOR for each specimen and a mean ultimate bending stress was determined for each formulation. Since the focus of this experimental study was on the creep-rupture behavior of the material, stress levels needed to be selected so as to promote failure within the time frame selected for testing. Thus, 95%, 90%, 80%, 70%, and 50% stress levels were targeted, and these percentages of the mean ultimate bending stress were calculated. Table 2-4 provides a summary of the calculated stresses for each formulation.

Table 2-4: *Static Bending Test Results and Targeted Stress Levels for Load-Duration Tests*

Formulation	Mean Ultimate Bending Stress (MPa)	COV (%)	95% Stress Level[1] (MPa)	90% Stress Level[1] (MPa)	80% Stress Level[1] (MPa)	70% Stress Level[1] (MPa)	50% Stress Level[1] (MPa)
PVC 50/50	41	2.8	39	37	33	29	21
HDPE 8	14	1.3	14	13	12	10	7
HDPE 67.5/32.5	18	3.9	17	16	14	12	9
HDPE 67.5 w/ MAPE	29	1.8	28	26	23	21	15

1. Percentage of Mean Ultimate Bending Stress

After initiating load-duration tests, subsequent testing investigating the effect of load rate (see Chapter Four) produced results differing from those obtained in the initial static bending tests. In this second series of tests, the same rate-of-load produced MOR values between 10 and 20 percent higher than those obtained from the initial static bending tests. The only differences between the two experiments were the type of test equipment used and the environment in which they were conducted. A computer-controlled hydraulic actuator was used in the original static bending tests, while a computer-controlled screw driven Instron 4400R testing machine was used for the load-rate tests. The initial static bending tests were performed in an open laboratory environment where temperature was not closely monitored or regulated because a controlled atmosphere facility capable of testing specimen of this size did not exist at the time. The subsequent load-rate tests were performed at a later date in a newly established large-scale temperature-controlled testing environment. Temperature was monitored during the load-rate experiment and found to fluctuate between 21°C (70° F) and 23°C (73° F), closely matching the conditions under which the duration-of-load tests were conducted. In an attempt to determine which values should be used as the basis for the stresses applied in the load-duration tests, the load-rate setup was used to perform a limited number of short-duration load-duration tests. Five specimens from three of the four formulations (the HDPE 67.5 w/ MAPE formulation was not available) were ramp loaded to the original 95 percent stress level and then a constant load was maintained until failure. The time-to-failure data from these experiments was found to agree well with the time-to-failure data from the load-duration tests for the same stress level, indicating that the setup and environmental conditions were quite similar. These results, combined with the knowledge that thermoplastics are subject to temperature effects (Haiar 2000), led to the conclusion that the MOR data from the load rate experiment was a more accurate representation of the static strength than that of the original static bending results. Given that several load-duration tests were already complete, it was decided that the stresses defined in Table 2-4 would continue to be used, but the stress ratios would be recalculated to reflect the increase in actual static strength. Table 2-5 gives the original and corrected stress ratios for each formulation.

Table 2-5: *Corrected Stress Ratios*

Formulation	**Original Stress Ratio**				
	95%	**90%**	**80%**	**70%**	**50%**
PVC	81.3%	77.0%	68.5%	59.9%	42.8%
HDPE 8	81.4%	77.1%	68.6%	60.0%	42.9%
HDPE 67.5	79.0%	74.9%	66.6%	58.2%	41.6%
HDPE 67.5 w/ MAPE	86.9%	82.4%	73.2%	64.1%	45.8%

LOAD-DURATION TESTS

The small coefficient of variation (COV) associated with the calculated material properties (see Table 2-4) of WPCs and the desire to obtain mean time-to-failure values made it possible to select a sample size of five for each stress ratio. Twelve test frames, capable of testing two specimens each, were used for the load-duration tests (Figures 2-3 and 2-4). The frames were specifically designed to conduct strong-axis creep and load-duration tests. Each frame provides lateral bracing, a support span of 1.83 m (6 ft), and two equal point loads applied with a spreader beam at the third points, or 610 mm (24 in.) from the supports. Concrete or steel weights hung from a 410-mm (16-in.) diameter pulley, providing an approximate 8:1 mechanical advantage, were used to supply the specified constant stress. Each specimen was subjected to a constant stress for 90 days, or until failure occurred.

Figure 2-3: *Load-Duration Test Frames*

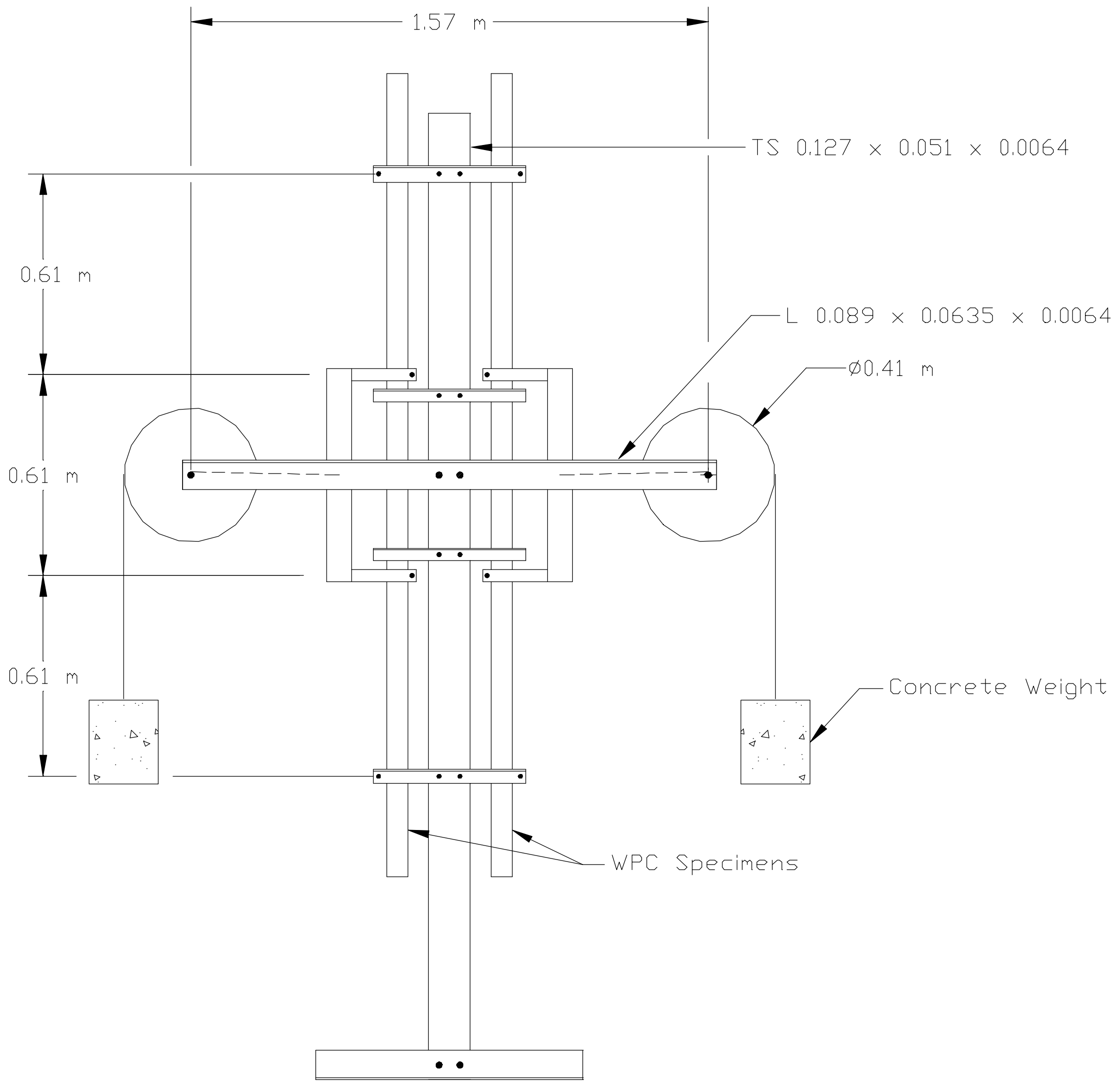

Figure 2-4: *Schematic of Load-Duration Test Frame*

A 254-mm (10-in.) linear position transducer, (UniMeasure LX-PA 10) accurate to +/- 0.13 mm (0.05 in.), was used to measure center span displacement. A typical setup for measuring displacement is shown in Figure 2-5. Data acquisition software recorded displacement versus time measurements on a hard drive every 30 seconds.

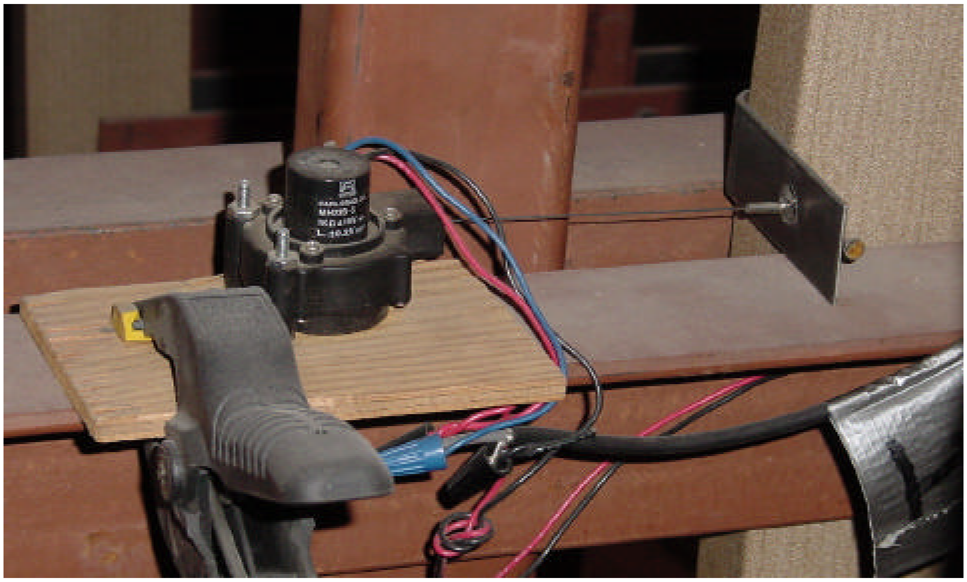

Figure 2-5: *Linear Position Transducer Setup*

LOAD RATE TESTS

It has been assumed that the load rate specified in ASTM D790 is appropriate for WPC members, although the standard is for the evaluation of unreinforced and reinforced plastics and the WPC formulations produced at WMEL for this project contained a minority percentage of plastic by mass. Thus, an experimental investigation was done to determine the effect, if any, of both higher and lower rates-of-load application on the flexural properties of WPCs. Five specimen from each formulation were ramp loaded to failure at three different rates. Table 2-6 lists the load rates applied along with the corresponding rate of strain in the outer fiber.

Table 2-6: *Load Rates Tested and Corresponding Strain Rates*

Rate-of-Load Application mm/min (in./min)	Rate-of-Strain in Outer Fiber mm/mm/min (in./in./min)
4.6 (0.18)	7.3×10^{-4} (7.3×10^{-4})
62.5 (2.46)	0.01 (0.01)
254 (10)	0.04 (0.04)

The test setup was similar to that used for the static bending tests. Major differences in setup included using a computer-controlled screw-driven 146 N (33 k) Instron 4400R testing machine and the inclusion of two additional linear position transducers to measure displacement at the points of load application. A schematic of the load rate test setup is given in Figure 2-6.

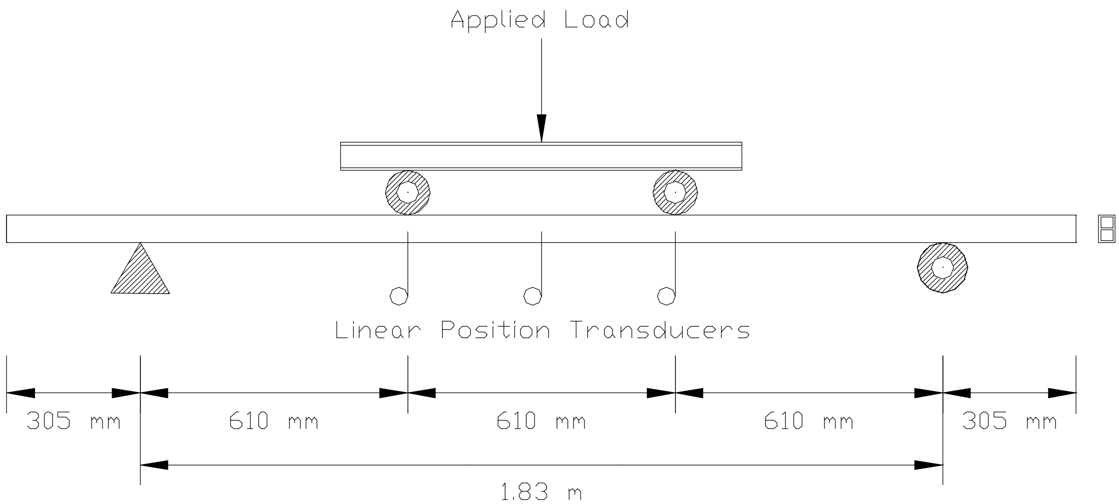

Figure 2-6: *Schematic of Load Rate Test Setup*

TEMPERATURE AND RELATIVE HUMIDITY

The static bending tests were performed in an open laboratory environment where temperature was not closely monitored or regulated. The ramifications of this were discussed previously in the section discussing the process for the determination of loads to be applied.

The laboratory space where the load-duration tests were conducted was maintained at a nearly constant 21°C (70° F) with a thermostat-controlled heating system. The tests were conducted primarily in the winter months; consequently, there was no need to provide thermostat-controlled cooling as well.

Load rate tests were conducted in a temperature-controlled environment where the temperature fluctuated between 21°C (70° F) and 23°C (73° F).

Previous experimental work by Adcock et al. (1999) conducted at WMEL on similar formulations indicated that WPC materials have a very low coefficient of diffusion and thus are not influenced by subtle changes in relative humidity. Therefore, relative humidity was not monitored during any portion of the experimentation.

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CHAPTER THREE

LOAD-DURATION BEHAVIOR OF WOOD-PLASTIC COMPOSITES[1]

ABSTRACT

The load-duration, or creep-rupture, behavior of wood and wood composite products has been studied extensively by numerous researchers, and simplified design procedures to account for creep effects are in place. However, the load-duration behavior of composite products made out of the combination of wood and plastic is not well understood or documented. Currently, wood-plastic composite (WPC) products are available on the commercial market, yet no standardized design procedures to account for creep or load-duration effects exist. Given the lack of understanding of the load-duration behavior of wood-plastic composites, a research effort was initiated to investigate the load-duration behavior of various wood-plastic composite formulations and to compare the observed behavior to that of solid sawn lumber. It was found that the wood-plastic composite formulations tested exhibited a more pronounced load-duration response than that of solid wood; however, the behavior trend was similar and was successfully modeled using an exponential damage rate model (EDRM) originally developed for solid wood. Existing procedures for developing load-duration design adjustment factors for wood were used to develop load-duration design adjustment factors specifically for the WPC formulations tested.

[1] To be submitted for review and possible publication in the *Journal of Materials in Civil Engineering*, American Society of Civil Engineers (ASCE).

INTRODUCTION

One of the important characteristics affecting many materials including wood, plastic, and wood-plastic composites used in structural applications is their time-dependent behavior. This behavior can be divided into two separate, yet related, phenomena known as creep and creep-rupture. Creep is the increase in deformation over time while subjected to a sustained load. Creep-rupture, or load-duration behavior, is the eventual failure of the material under sustained load due to increased deformation over time (creep). Both have a significant effect on wood-plastic composite (WPC) product performance and are important issues to consider in structural applications (Sain et al., 2000). However, from a design standpoint, the creep-rupture behavior of a material is of particular interest due to collapse and life-safety implications.

The load-duration behavior of composite products made out of the combination of wood and plastic is not well understood or documented. Currently, wood-plastic composite products are available on the commercial market, yet no standardized procedures to test for or to account for load-duration effects exist. With the emergence of numerous wood-based composites, including WPC products, the American Society for Testing and Materials (ASTM) Committee D-7 has initiated the development of a standardized set of procedures and performance criteria for evaluating load-duration behavior of wood and wood-based products (ASTM 2001). The standard was in the early draft stages at the time this research was conducted, and a concerted effort was made to keep abreast of its development, adhere to the procedures outlined in it whenever possible, and to evaluate the WPC formulations tested against the performance criteria supplied.

Given the broad spectrum of work that must be done before the creep and load-duration behavior of WPC materials is understood, it was necessary to carefully define the scope of work for this project. Thus, the focus of this research effort was to evaluate the load-duration behavior of near full-sized wood-plastic composite structural products and to propose design procedures to account for load-duration effects that are compatible with current design procedures for wood and traditional wood composite products.

BACKGROUND

The creep and creep-rupture, or load-duration, behavior of wood and traditional wood composite products has been studied extensively by numerous researchers. Several comprehensive reviews of load-duration research and damage modeling for wood and wood products exist (Karacabeyli, 1988; Fridley, 1992; Fridley et al., 1995; Nelson, 2000), thus only research directly relevant to this experimental study will be reviewed herein.

Wood (1951) collected time-to-failure data for small clear specimens of Douglas-fir subjected to constant center span loads ranging from 60 to 95 percent of the short-term strength observed in static tests of matched samples. A hyperbolic model was then fit to the time-to-failure data assuming a stress threshold below which the specimen would not fail. Equation 3-1a gives the general form of the model and Equation 3-1b, better known as the "Madison curve," gives the model calibrated by Wood:

$$t_f = \frac{1}{A(\sigma - \sigma_0)^B} \tag{3-1a}$$

$$\sigma = \frac{1.084}{t_f^{\;0.04635}} + 0.183 \tag{3-1b}$$

where σ is the ratio of applied stress to the static test strength, t_f is the time-to-failure (in seconds for Eqn. 3-1b), σ_0 is a stress threshold, and A and B are model constants. The Madison curve, as defined above in Equation 3-1b, is the basis for the load-duration adjustment factors defined in the *National Design Specification for Wood Construction* (AF&PA 1997).

Barrett and Foschi (1978) developed two damage accumulation models based on the data collected by Wood (1951). The first model (Equations 3-2a and 3-2b) is capable of modeling creep-rupture data of a linear form (where time-to-failure is a linear function of stress), which they found to adequately represent the vast majority of creep-rupture data for wood. It can be written as follows:

$$\frac{d\alpha}{dt} = A(\sigma - \sigma_o)^B \alpha^C \qquad \text{if } \sigma > \sigma_o \tag{3-2a}$$

$$\frac{d\alpha}{dt} = 0 \qquad \text{if } \sigma \le \sigma_o \tag{3-2b}$$

where α is a state variable representing damage ranging from zero, meaning no damage is present, to one, corresponding to failure; $d\alpha/dt$ is the rate of damage accumulation with respect to time; σ is the ratio of applied stress to static test strength; σ_o is a stress threshold below which no damage occurs, and A, B, and C are model constants determined from test data.

The second Barrett and Foschi (1978) model (Equations 3-3a and 3-3b) is able to model creep-rupture data of a bilinear form (where time-to-failure is a bilinear function of stress), and was found to provide a better fit to the constant load data of small clear specimens. It is similar to the first model and takes the following form:

$$\frac{da}{dt} = A(s - s_o)^B + Ca \quad \text{if } s > s_o \qquad (3\text{-}3a)$$

$$\frac{da}{dt} = 0 \quad \text{if } s \le s_o \qquad (3\text{-}3b)$$

where all parameters are as defined previously.

Gerhards (1977, 1979) proposed an exponential cumulative damage approach to modeling load-duration behavior. Again, data from tests of small clear specimens was used. The model (Equation 3-4), which evaluates the amount of damage accumulated using an exponential decay format, commonly referred to as an exponential damage rate model, or EDRM, is given below:

$$\frac{da}{dt} = \exp(-A + Bs) \qquad (3\text{-}4)$$

where all parameters are as defined previously. Further work by Gerhards and Link (1987) included calibrating the EDRM to load-duration data from tests of Douglas-fir 2 x 4s (38 mm x 89 mm), proving that the model applied to not only small clear specimens, but to full-sized lumber as well.

Building upon the second Barrett and Foschi model, yet taking a somewhat different approach, Foschi and Yao (1986) proposed a more complicated damage accumulation model (Equation 3-5). Unlike the previously developed models, the Foschi and Yao model is a function of the actual applied stress as opposed to a function of the applied stress ratio. Their model can be expressed as:

$$\frac{da}{dt} = A(t - t_o)^B + Ca(t - t_o)^D \qquad (3\text{-}5)$$

where τ is the applied stress, τ_o is a stress threshold, D is an additional model constant determined from test data, and all other model parameters are as defined previously. Foschi and Yao concluded that their model provided a more accurate description of the load-duration behavior of lumber than the second Barrett and Foschi model, however solving for five model constants in a consistent and accurate manner proved to be troublesome.

Gerhards (1988, 1991) continued investigating the load-duration behavior of full-sized lumber and found that the allowable bending stress for lumber seemed to be non-conservative for design loads that really exist for the design duration. Based on the data obtained from previous tests and following the methods used in developing the NDS adjustment factors, Gerhards (1988) used his own load-duration equations to propose modifications to the load-duration adjustment factors used in the design of timber structures. These proposed adjustment factors resulted in lower design values regardless of the design load duration under consideration. Gerhards also concluded that there was no evidence to support the claim of a stress threshold below which no damage occurred. This discovery was in direct contrast with the models developed previously by Wood (1951), Barrett and Foschi (1978), and Foschi and Yao (1986). Additionally, Gerhards (1991) concluded that shorter duration of load effects should be the primary focus for those concerned with designing safe timber structures.

Very little documentation exists detailing research focusing on the load-duration behavior of wood-plastic composites. Sain et al. (2000) acknowledge that due to the nature of the material and its complexity there is no general agreement, strategy, or tactic of how to experimentally measure the creep behavior of these composite materials. Sain et al. (2000) focused on the creep fatigue behavior of engineered wood fiber and plastic compositions. The formulations tested were polyvinyl chloride (PVC), polyethylene (PE), or polypropylene (PP) based and contained a constant 30 percent wood fiber by weight. The effects of including maleated polyethylene or polypropylene as a coupling agent were also investigated. Coupon level flexural creep tests were conducted with stress ratios ranging from 10 to 50 percent. Sain et al. (2000) found that creep behavior was a strong function of the loading condition and temperature. PVC formulations were found to be especially sensitive to temperature changes and PE formulations, coupled or uncoupled, showed very low creep resistance. Coupled PP formulations were found to be more resistant to instantaneous creep than uncoupled formulations, however, the transient creep behavior of both was only marginally better than virgin PP.

Xu et al. (2001) examined the creep behavior of wood-filled polystyrene (PS)/high density polyethylene (HDPE) blends. The formulations consisted of 10% to 40% wood flour melt blended with various ratios of the PS/HDPE blend. Three-point bending creep tests were performed on flat rectangular 2 x 12 x 60 mm bars. They found that the addition of wood flour increased the modulus of elasticity and also tended to decrease the creep speed.

Pooler (2001) examined the creep behavior of a high density polyethylene (HDPE) formulation identical to the HDPE 8 formulation reported on herein. Creep tests at 23 °C on 200 x 25 x 13 mm coupons were performed at stress levels ranging from 30% to 90% of ultimate stress. Pooler found that no damage occurred at or below a stress level of approximately 43% of the ultimate stress obtained from static tests.

Despite the valuable insight provided by Sain et al. (2000), Xu et al. (2001), and Pooler (2001) into the creep behavior of WPC products, uncertainty remains in regards to the load-duration behavior of WPC products. Thus, an experimental research program was initiated to characterize the load-duration behavior of WPC materials.

MATERIALS

Four wood-plastic composite formulations were selected for evaluation. The first formulation was produced with polyvinyl chloride (PVC), and the remaining three formulations were produced with high-density polyethylene (HDPE). The HDPE 8 formulation contained the following processing aides: 2% zinc stearate (Ferro Chemicals Synpro DLG-20B) and 1% EBS wax (GE Specialty). Another of the three HDPE formulations contained an ethylene-maleic anhydride polymer, MAPE, which is a commercially available coupling agent added to strengthen the bond at the interface between the polyethylene and wood fibers. Table 3-1 provides the material composition of each formulation and gives the percentage used by weight.

Table 3-1: *Formulation Materials and Percentages*

Formulation	% Flour	Wood Flour Type	% Plastic	Plastic Type	Additives
PVC	50	Ponderosa Pine (AWF #4020)	50	PVC Compound (Georgia Gulf) (3014 nat 00)	None
HDPE 8	58	Maple (AWF #4010)	31	HDPE (Equistar) (LB 0100 00)	8% Ceramic Talc (Suzqrite) 3% Processing Aides
HDPE 67.5	67.5	Maple (AWF #4010)	32.5	HDPE (Equistar) (LB 0100 00)	None
HDPE 67.5 w/ MAPE	67.5	Maple (AWF #4010)	30.95	HDPE (Equistar) (LB 0100 00)	1.55% MAPE (AlliedSignal) (575A1)

All materials were dry blended in a 1.2-m (4-ft) diameter drum mixer in 20-kg (44-lb) batches. The dry mixture was then loaded into the hopper of a conical counter-rotating twin screw extruder (Cincinnati-Milacron E55) and a two-box cross section was extruded using a stranding die (Laver, 1996) and cut into 2.44-m (8-ft) lengths. Process temperatures are provided in Table 3-2.

Table 3-2: *Extrusion Process Temperatures*

Formulation	Process Temperature (^{o}C)				
	Barrel	Screw	Die Zone 1	Die Zone 2	Die Zone 3
PVC	168	140	174	174	160
HDPE 8	163	163	171	171	171
HDPE 67.5	163	163	163	171	143
HDPE 67.5 w/ MAPE	163	163	163	171	143

Figure 3-1 shows the two-box cross section and Table 3-3 summarizes the nominal section dimensions and selected properties.

Figure 3-1: *Two-Box Cross Section*

Table 3-3: *Nominal Two-Box Section Dimensions and Properties*

Property	Value
Depth	89 mm (3.5 in.)
Width	36 mm (1.40 in.)
Wall Thickness	5 mm (0.20 in.)
Cross-Sectional Area	1290 mm^2 (2.00 $in.^2$)
Moment of Inertia (Strong Axis)	1.05×10^6 mm^4 (2.52 $in.^4$)

STATIC BENDING TESTS

Twenty-eight specimens were weighed to the nearest milligram on a digital scale and cross-sectional dimensions were measured to the nearest 0.025 mm (0.001 in.) with digital calipers. Procedures outlined by Haiar (2000) for determining strong-axis modulus of rupture (MOR) for structural wood-plastic composite beams were followed. The test method specifies that ASTM D198 (1998), a standard test method for determining properties of structural lumber, be followed with two exceptions: load rate and span length. Haiar recommended that the load rate be calculated according to ASTM D790 (1997), a standard test method for determining flexural properties of unreinforced and reinforced plastics. The standard specifies that the load be applied such that the rate of strain in the outer fiber is 0.01 mm/mm/min. (0.01 in./in./min.). Based on nominal section dimensions, this corresponded to a load rate of 62.5 mm/min. (2.46 in./min.). Haiar (2000) recommended that the ratio of support span length to radius of gyration be used to determine the test span; however, a span consistent with that of the load-duration test frames, 1.83 m (6 ft), was used. Similarly, the load was applied at third points, or 610 mm (24 in.) from the end reactions to be consistent with the load-duration frames (see subsequent discussion in this chapter). Lateral bracing was provided along the span to prevent lateral-torsional buckling.

Each specimen was subjected to a ramp load applied through a computer controlled hydraulic actuator until failure occurred. A spreader beam was used to evenly distribute the single point load of the actuator into the two point loads applied to the specimen. Center span displacement was measured using a linear position transducer accurate to +/- 1.27 mm (0.05 in.). A computerized data acquisition system recorded load-displacement data, maximum load, and time-to-failure for each specimen.

DETERMINATION OF LOADS

Cross-sectional dimensions and maximum load data from static bending tests were used to calculate the modulus of rupture (MOR) for each specimen and a mean ultimate bending stress was determined for each formulation. Since the focus of this experimental study was on the creep-rupture behavior of the material, stress levels needed to be selected so as to promote failure within the time frame selected for testing. Thus, 95%, 90%, 80%, 70%, and 50% stress levels were targeted, and these percentages of the mean ultimate bending stress were calculated. Table 3-4 provides a summary of the calculated stresses for each formulation.

Table 3-4: *Static Bending Test Results and Targeted Stress Levels for Load-Duration Tests*

Formulation	Mean Ultimate Bending Stress (MPa)	COV (%)	95% Stress Level[1] (MPa)	90% Stress Level[1] (MPa)	80% Stress Level[1] (MPa)	70% Stress Level[1] (MPa)	50% Stress Level[1] (MPa)
PVC 50/50	41	2.8	39	37	33	29	21
HDPE 8	14	1.3	14	13	12	10	7
HDPE 67.5/32.5	18	3.9	17	16	14	12	9
HDPE 67.5 w/ MAPE	29	1.8	28	26	23	21	15

1. Percentage of mean ultimate bending stress

After initiating the load-duration tests, subsequent testing investigating the effect of load rate (see Chapter Four) produced results differing from those obtained in the initial static bending tests. In this second series of tests, the same rate-of-load produced MOR values between 10 and 20 percent higher than those obtained from the initial static bending tests. The only differences between the two experiments were the type of test equipment used and, more importantly, the environment in which the tests were conducted. A computer-controlled hydraulic actuator was used in the initial static bending tests, while a computer-controlled screw driven testing machine was used for the load-rate tests. The initial static bending tests were performed in an open laboratory environment where temperature was not closely monitored or regulated because a controlled atmosphere facility capable of testing specimen of this size did not exist at the time. The subsequent load-rate tests were performed at a later date in a newly established large-scale temperature-controlled testing environment. Temperature was monitored during the load-rate experiment and found to fluctuate between 21°C (70° F) and 23°C (73° F), closely matching the conditions under which the duration-of-load tests were conducted. In an attempt to determine which values should be used as the basis for the stresses applied in the load-duration tests, the load-rate setup was used to perform a limited number of short-duration load-duration tests. Five specimens from three of the four formulations (the HDPE 67.5 w/ MAPE was not available) were ramp loaded to the original 95 percent stress level and then a constant load was maintained until failure. The time-to-failure data from these experiments was found to agree well with the time-to-failure data from the load-duration tests for the same stress level, indicating that the setup and environmental conditions were quite similar. These results, combined with the knowledge that thermoplastics are subject to temperature effects (Haiar, 2000), led to the conclusion that the MOR data from the load rate experiment was a more accurate representation of the static strength than that of the original static bending tests. Given that several load-duration tests were already complete, it was decided that the stresses defined in Table 3-4 would continue to be used, but the stress ratios would be recalculated to reflect the increase in actual static strength. Table 3-5 gives the original and corrected stress ratios for each formulation.

Table 3-5: *Corrected Stress Ratios*

Formulation	Original Stress Ratio				
	95%	**90%**	**80%**	**70%**	**50%**
PVC	81.3%	77.0%	68.5%	59.9%	42.8%
HDPE 8	81.4%	77.1%	68.6%	60.0%	42.9%
HDPE 67.5	79.0%	74.9%	66.6%	58.2%	41.6%
HDPE 67.5 w/ MAPE	86.9%	82.4%	73.2%	64.1%	45.8%

LOAD-DURATION TESTS

The small coefficient of variation (COV) associated with the calculated material properties (see Table 3-4) of WPCs and the desire to obtain mean time-to-failure values made it possible to select a sample size of five for each stress ratio. Twelve test frames, capable of testing two specimens each, were used for the load-duration tests. The frames were specifically designed to conduct strong-axis creep and load-duration tests. Each frame provides lateral bracing, a support span of 1.83 m (6 ft), and two equal point loads applied with a spreader beam at the third points, or 610 mm (24 in.) from the supports. Concrete or steel weights hung from a 410-mm (16-in.) diameter pulley, providing an approximate 8:1 mechanical advantage, were used to supply the specified constant stress. Each specimen was subjected to a constant stress for 90 days, or until failure occurred. A 254-mm (10-in.) linear position transducer, accurate to +/- 0.13 mm (0.05 in.), was used to measure center span displacement. Data acquisition software recorded displacement versus time measurements on a hard drive every 30 seconds.

The laboratory space where the load-duration tests were conducted was maintained at a nearly constant 21°C (70° F) with a thermostat-controlled heating system. The tests were conducted primarily in the winter months; consequently, there was no need to provide thermostat-controlled cooling as well.

RESULTS

A displacement versus time curve was generated for each specimen. Figures 3-2 through 3-5 illustrate a typical curve for each formulation at the lowest stress level tested.

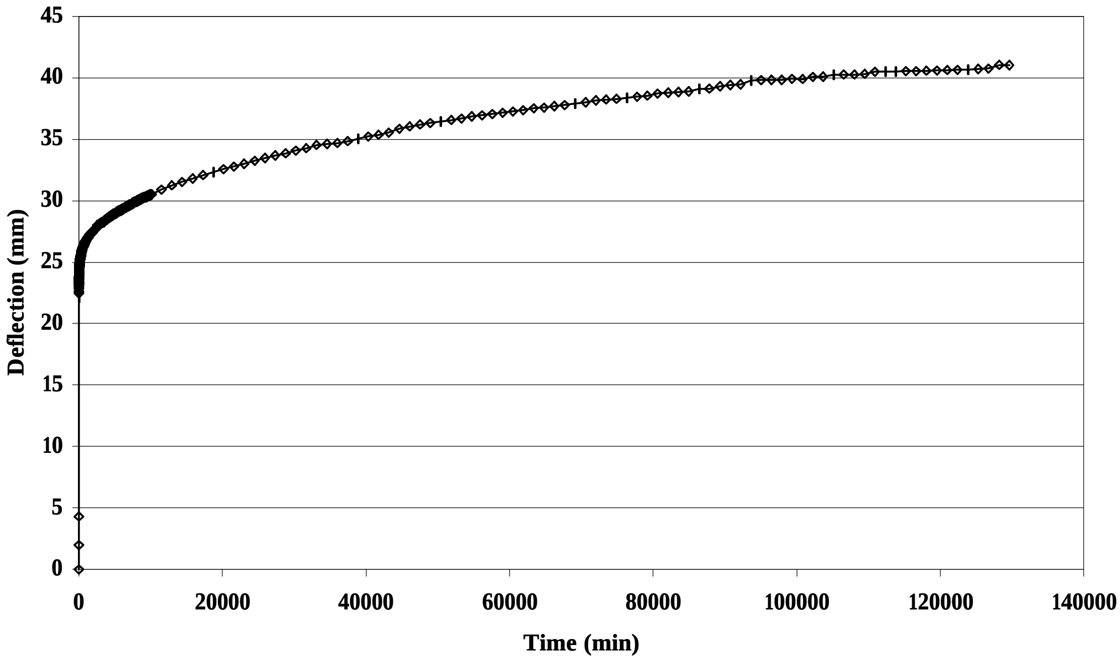

Figure 3-2: *Deflection vs. Time for PVC at 42.8% of Mean Ultimate Bending Stress*

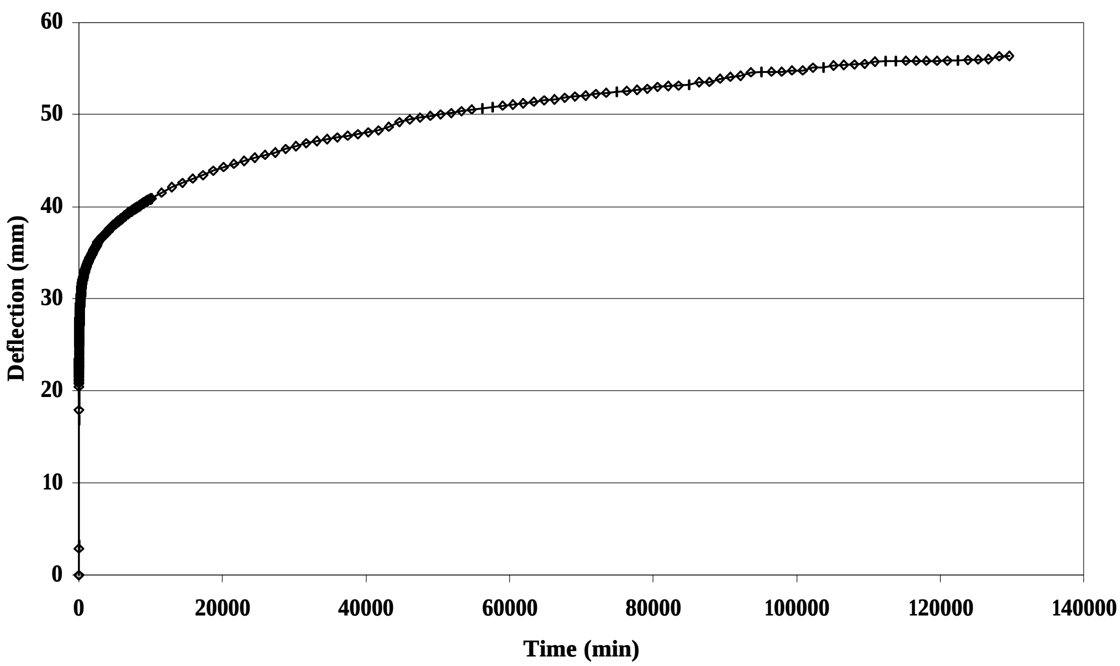

Figure 3-3: *Displacement vs. Time for HDPE 8 at 42.9% of Mean Ultimate Bending Stress*

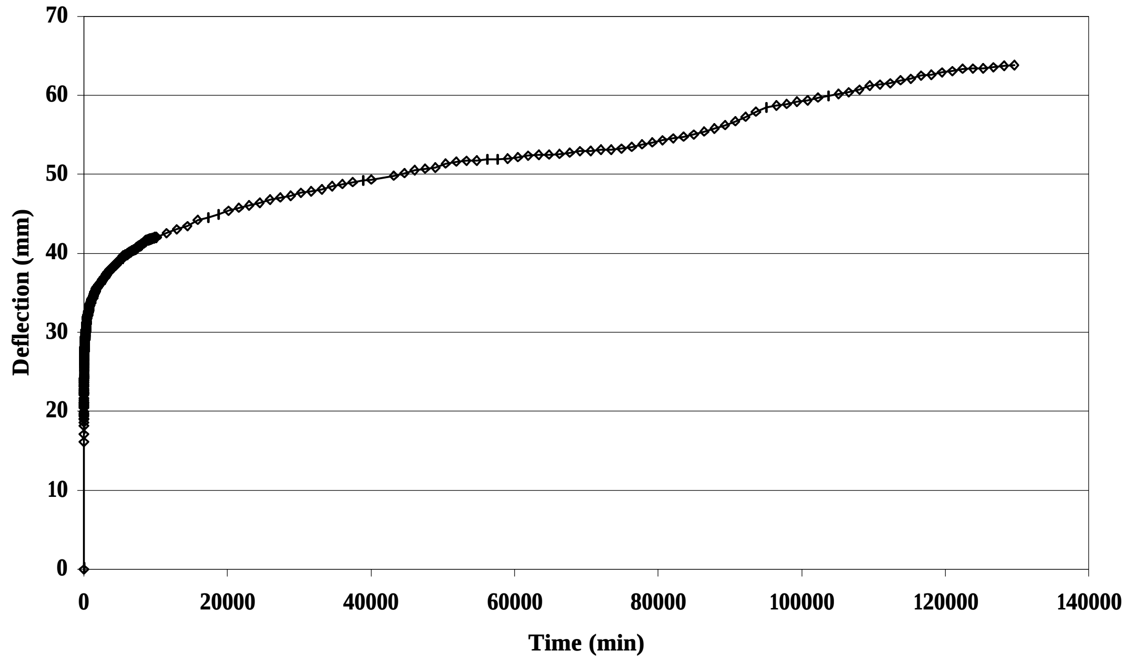

Figure 3-4: *Displacement vs. Time for HDPE 67.5 at 41.6% of Mean Ultimate Bending Stress*

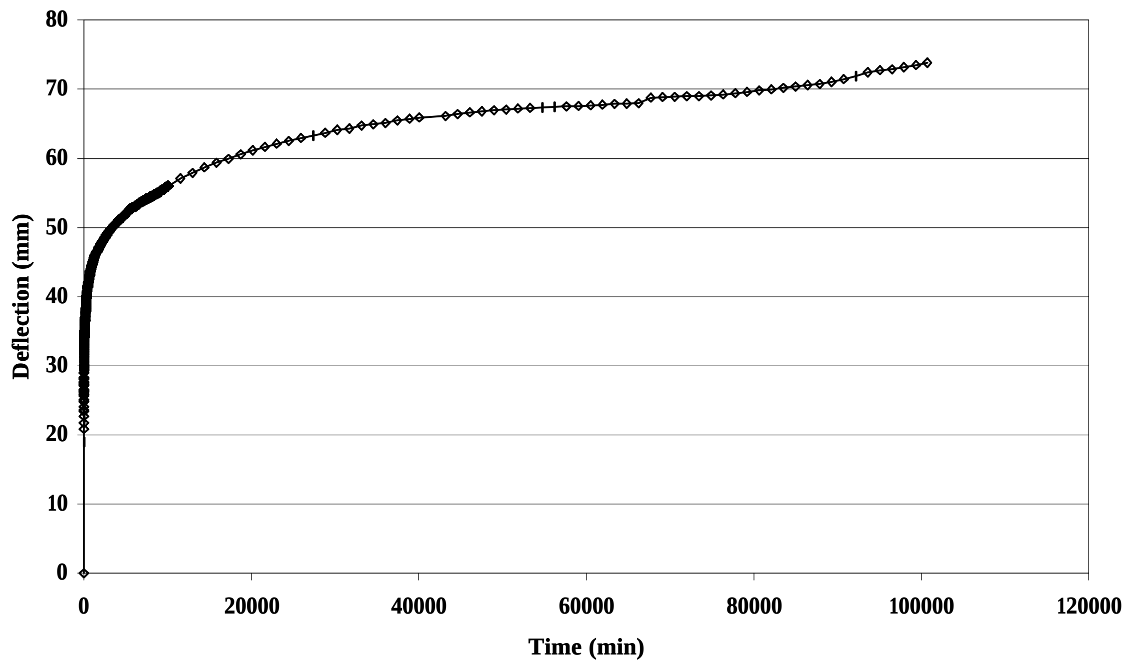

Figure 3-5: *Displacement vs. Time for HDPE 67.5 w/ MAPE at 45.8% of Mean Ultimate Bending Stress*

In general, the displacement-time behavior trend of the WPC formulations tested is comparable to the trend observed for solid sawn lumber at similar stress levels (Fridley et al., 1992a). The observed response included similarities of an initial elastic deflection followed by a primary creep phase. WPCs, however, produce a tendency toward a prolonged viscoelastic primary creep phase, and an apparently low contribution of pure viscous behavior, which occurs in the secondary creep phase. The displacement versus time curves provide a graphical means of examining the response of the materials to constant stress over time. Of particular interest is the rate at which the material deforms with respect to time, also known as the rate of creep. Examination of Figs. 3-2 through 3-5 shows that the rate of creep decreases over time for the PVC and HDPE 8 formulations, and that the rate of creep is decreasing for a period of time, but then increases for the HDPE 67.5 and HDPE 67.5 w/ MAPE formulations followed by a decrease in rate over the final interval for the HDPE 67.5 formulation. For the HDPE 67.5 w/ MAPE formulation, three of the five specimens failed prior to reaching the time at which the increased creep rate was observed in the other two specimens. Average creep rates for each formulation at the lowest stress level were calculated over specific time intervals and are listed in Table 3-6.

Table 3-6: *Average Rate of Creep (mm/hour) Over Selected Time Intervals*

Formulation	**Time interval (1000 minutes)**			
	40-60	**60-80**	**80-100**	**100-120**
PVC	0.0058	0.0043	0.0042	0.0017
HDPE 8	0.0071	0.0060	0.0067	0.0029
HDPE 67.5	0.0066	0.0046	0.0158	0.0104
HDPE 67.5 w/ MAPE[1]	0.0049	0.0057	0.0146	N/A

1. Two of the five specimens failed prior to the 40,000-minute interval, one addition specimen failed during the interval, and the remaining two specimen failed during the 80,000-minute interval.

Plots of the applied stress ratio (SR) versus the time-to-failure are the traditional method for evaluating of the load-duration performance of a material and for developing adjustment factors. Figures 3-6 through 3-9 show the time-to-failure plots for each formulation. For convenience, the time axis is plotted on a logarithmic scale. An arrow next to a data point indicates that the specimen did not fail during the 90-day test duration. Additionally, the plots contain two reference lines: Gerhards' EDRM (1988) calibrated for Select Structural Douglas-fir 2 x 4s, and the Madison curve (Wood 1951). Finally, the plots contain curves generated by performing a least squares regression fit of the data to both Gerhards' EDRM and Wood's model. Regression was performed using only data points resulting from specimen failure; that is, if a specimen did not fail during the 90-day test period, the data point was excluded from the regression analysis. Constants for both models are provided in Table 3-7. It should be noted that a regression analysis was performed using all data points and that the results differed only slightly from the analysis performed using only data from specimen failure.

Table 3-7: *Model Constants*

Formulation	**Gerhards' EDRM**		**Wood's Model**		
	A	**B**	**A**	**B**	**σ_0**
PVC	25.265	31.782	441.600	8.713	0.466
HDPE 8	22.137	23.724	0.005	13.240	0.000
HDPE 67.5	22.840	26.491	0.900	8.130	0.341
HDPE 67.5 w/ MAPE	22.319	25.681	0.120	14.500	0.050

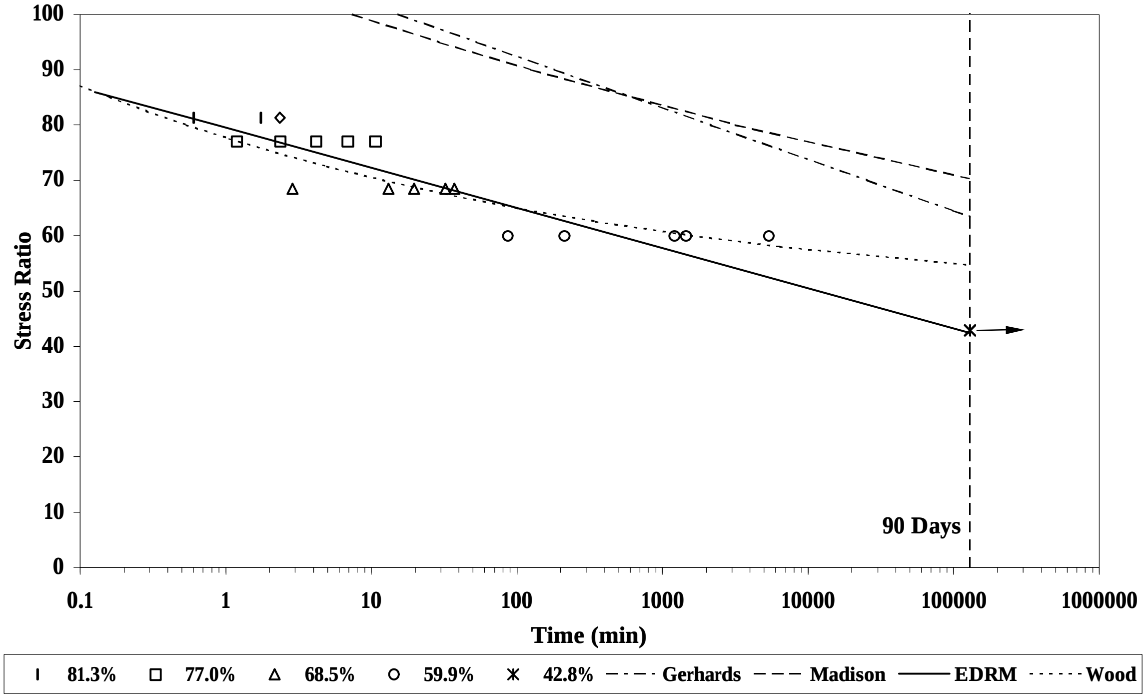

Figure 3-6: *Time-to-Failure Plot: PVC*

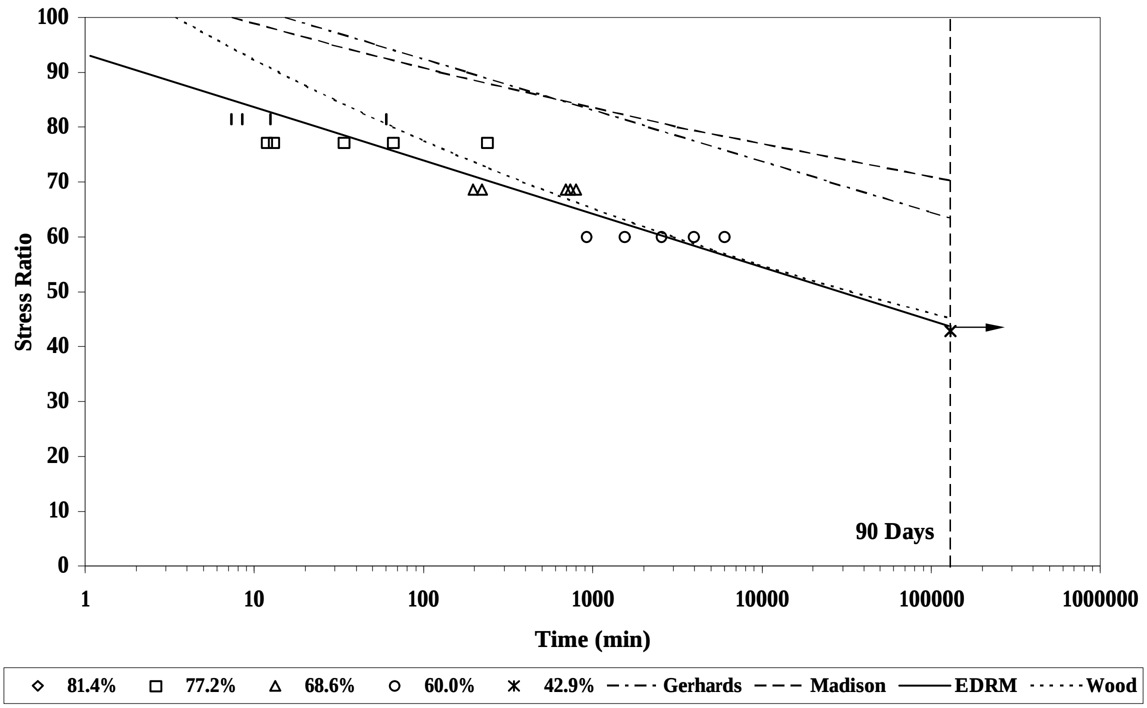

Figure 3-7: *Time-to-Failure Plot: HDPE 8*

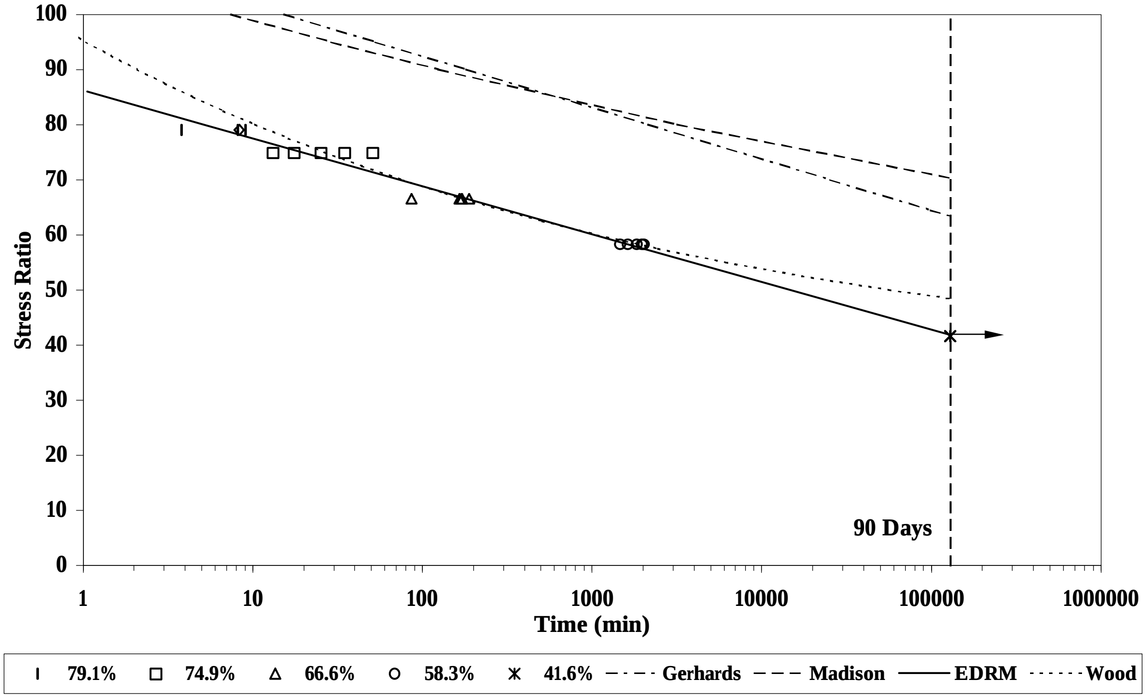

Figure 3-8: *Time-to-Failure Plot: HDPE 67.5*

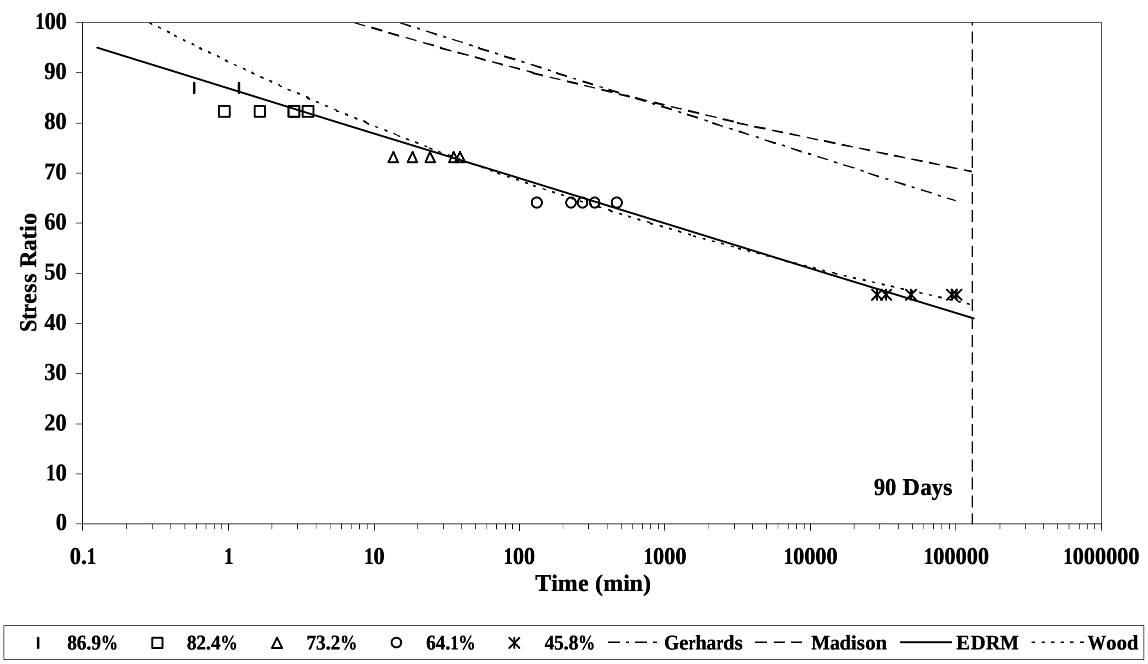

Figure 3-9: *Time-to-Failure Plot: HDPE 67.5 w/ MAPE*

It is obvious from a visual examination of the plots that the load-duration performance of the WPC formulations tested differs significantly in many aspects from the load-duration performance of solid sawn lumber. This is evident in the relatively short times to failure when compared to the solid lumber data represented by the two calibrated models.

The two models, Gerhards' EDRM (1979) and Wood's hyperbolic model (1951), were both developed using data obtained from tests conducted on lumber; however, they both provide a reasonably good fit to the WPC data, with the EDRM providing the best fit. Goodness of fit was determined by evaluating the standard error of the estimate and by visual inspection. Standard error of the estimate and the coefficient of determination are given in Table 3-8.

Table 3-8: *Standard Errors of the Estimate and Coefficients of Determination*

Formulation	Standard Error of the Estimate		Coefficient of Determination	
	EDRM	**Wood's**	**EDRM**	**Wood's**
PVC	1.468	62618	0.779	0.357
HDPE 8	0.895	59974	0.841	0.634
HDPE 67.5	0.411	6855	0.967	0.980
HDPE 67.5 w/ MAPE	1.037	887880	0.933	0.762

It is important to note that, although the model constants A and B (Table 3-8) for the EDRM are different than those calculated for solid lumber, the regression statistics are quite similar to those presented by Gerhards (1988) and Fridley et al. (1992b) from tests of Douglas-fir. This indicates that the EDRM represents the load-duration response of WPCs equally well as that of solid wood.

One of the difficulties encountered with Wood's model; however, is the assumption of a stress threshold below which no damage occurs. Given that high-stress, short-duration tests were the focus of this research, it was not possible to determine if or at what stress a threshold may exist. Pooler (2001) found a threshold at a stress ratio of approximately 43% in tests conducted on HDPE 8 coupons, however replacing the σ_o parameter with this constant did not improve the model fit or regression statistics. In fact, the model fit and regression statistics were poorer than when the parameter was determined through the regression analysis. For the remaining formulations, the uncertainty surrounding the existence and location of a threshold made estimating model parameters quite difficult and may partially account for the poor fit to the data. Additionally, the data does not lie in a pattern characteristic of a hyperbolic curve, so Wood's model provides a good fit to certain regions of the data, but returns a poor fit at one or both tail regions. The linearity of the data, when plotted on a semi-log scale, results in a good fit for an exponential model such as Gerhards' EDRM. Figure 3-10 compares the EDRM curves generated for each formulation and contains the select structural EDRM from Gerhards (1988) as a point of reference.

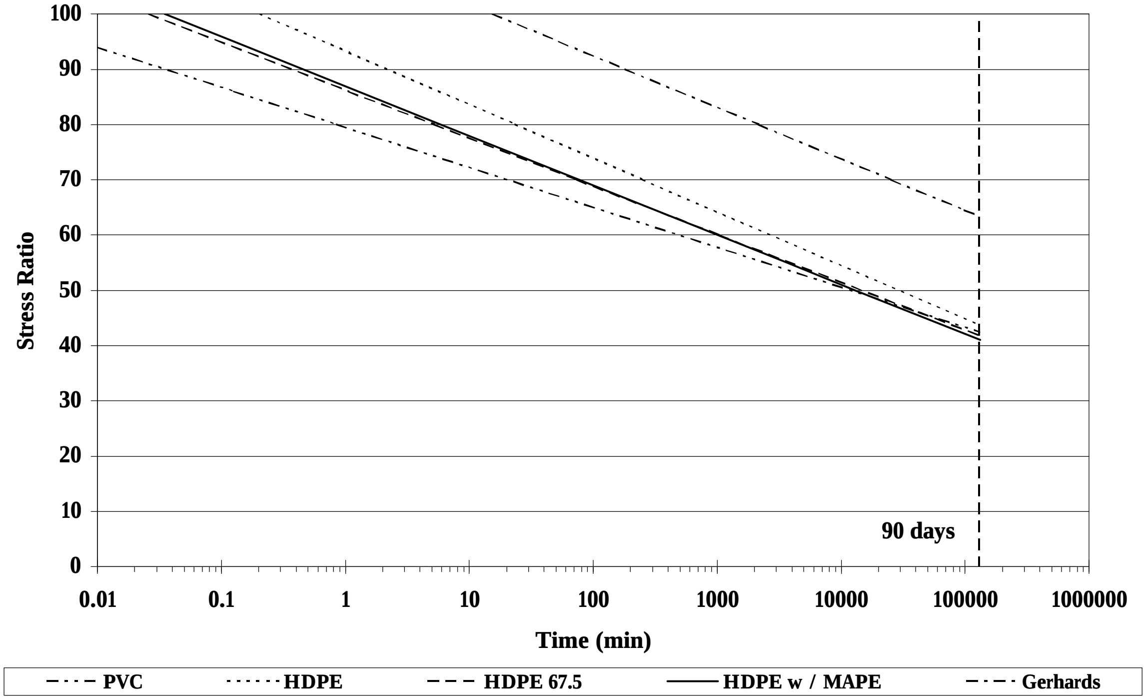

Figure 3-10: *EDRM Comparison*

Examination of the model calibrated by Gerhards (1988) for solid sawn lumber reveals that the curve crosses the 100% SR line at approximately 15 minutes, which corresponds to the time-to-failure observed in the ramp load static tests. Examination of the intercept of the EDRMs generated through least squares regression yields intercept values ranging between 0.0015 and 0.20 minutes, while ramp load static test time-to-failure values ranged from 0.80 to 1.03 minutes. This suggests that the extremely short duration response of the material is not well modeled with the Gerhards damage accumulation model. However, this form of the damage accumulation model assumes a condition of constant stress, not a ramp loading condition where stress is variable; thus, it is not unexpected that a difference in predicted failure times was observed. The difference between the two results can be explained from an examination of the damage accumulation for the two types of tests. Load-duration, or constant stress, tests have a constant rate of damage accumulation that begins immediately after the stress is applied. If the stress level is high, then the amount of damage accumulated over a short period of time is quite large with respect to the amount of damage necessary to induce failure. However, for a ramp load test, the rate of damage accumulation is exponentially increasing with stress level, starting at zero, and the cumulative amount of damage is very small for the majority of the test when compared to the amount of damage necessary to induce failure. Only when stresses near ultimate, does any substantial amount of damage accumulate. Thus, it can be expected that constant stress tests will yield shorter durations for high stresses than a ramp load test unless the ramp load is applied at a rate significantly higher than that specified for static testing. This concept is fully discussed by Fridley and Rosowsky (1994). Even without the previous explanation, the setback of a discrepancy between the model and ramp load data is a small one and can be considered inconsequential since the long-term behavior is the primary focus of interest. It should be noted that Fridley (1990) observed similar problems with the damage model not returning exact values for ramp loading and concluded that the drawback is not a crucial fault in the model since short-term behavior can be handled by other traditional means.

It appears, in Figs. 3-6 through 3-9, that the EDRM curves for the WPC formulations are a parallel shift of the EDRM curve for Douglas-fir. This would indicate that the behavior is quite similar to that of solid wood and that the difference in performance could be accounted for by reducing the published design value by a scaling factor. This reduction would shift the EDRM curve so that it overlays the EDRM curve for Douglas-fir, and consequently, the load-duration adjustment factors suggested by the NDS could be applied to WPCs as well. Unfortunately, this is not the case. Although the difference between the WPC EDRMs and the Douglas-fir EDRM appears to be a nearly parallel shift, one must recall that the time axis is plotted on a logarithmic scale. Shifting the EDRM curves so that they overlay the Douglas-fir EDRM reveals that a rotation of the curves occurs in addition to the shift. The presence of a rotation implies that the load-duration behavior of the two materials is not exactly the same. Thus, two options are available for accounting for the load-duration behavior of WPCs in design. First, a new set of adjustment factors can be determined using existing methods that are used for solid wood products. The load-duration behavior of WPCs is similar enough to that of solid wood that the generalized procedures in ASTM D245 (1993) can still be applied. Or, if consistency with the existing *National Design Specification for Wood Construction* (NDS) (AF&PA 1997) factors is targeted, the published bending strength values can be reduced by a scaling factor so that the WPC EDRM curves intersect the Douglas-fir EDRM at the ten-year duration. This results in accurate predictions of strength at the ten-year duration, and increasingly conservative predictions of strength for shorter durations.

A comparison of the load-duration behavior of the WPCs tested and that of solid sawn lumber indicated that the behaviors were similar, thus allowing load-duration factors to be determined using methods developed for wood. Factors listed in the NDS are based on the procedures outlined in ASTM D245. The method consists of establishing allowable design values based on a normal duration of ten years. A predictive model is extrapolated out to ten years and a reference stress ratio (SR) is established. This reference SR is the stress that can be withstood for a “normal,” ten-year, duration. The allowable value, typically obtained using a 5% exclusion limit, is reduced by dividing it by the reciprocal of the reference ten-year SR as is shown in Equation 3-6:

$$f_{10} = \frac{f_{allow}}{(1/SR_{10})} \tag{3-6}$$

where f_{10} is the design value that will be published for a 10-year duration, f_{allow} is the allowable, or 5% exclusion limit value obtained from test results, and SR_{10} is the reference ten-year SR. It is important to note that, for wood, a 1.3 safety factor is also applied to the allowable value before it is published. A load-duration adjustment factor of 1.0 is then assigned to loads with a ten-year duration. Interpolation along the curve of the predictive model is used to determine other stress ratios for given durations, and these values are then normalized by the ten-year SR to obtain the corresponding adjustment factors.

The generated EDRM curves for the WPCs and the procedures in ASTM D245 (1993) were used to develop load-duration factors for the four WPC formulations tested. Figure 3-11 graphically presents the adjustment factors for various load durations between two minutes and ten years and also includes the NDS curve. Table 3-9 lists the proposed load-duration adjustment factors for each formulation along with the adjustment factors published in the NDS (AF&PA 1997) for wood over the same range of durations. Figure 3-11 shows that it would be possible to use the NDS design factors for the WPC formulations tested, but the factors become increasingly and overly conservative as the design duration of loading becomes shorter.

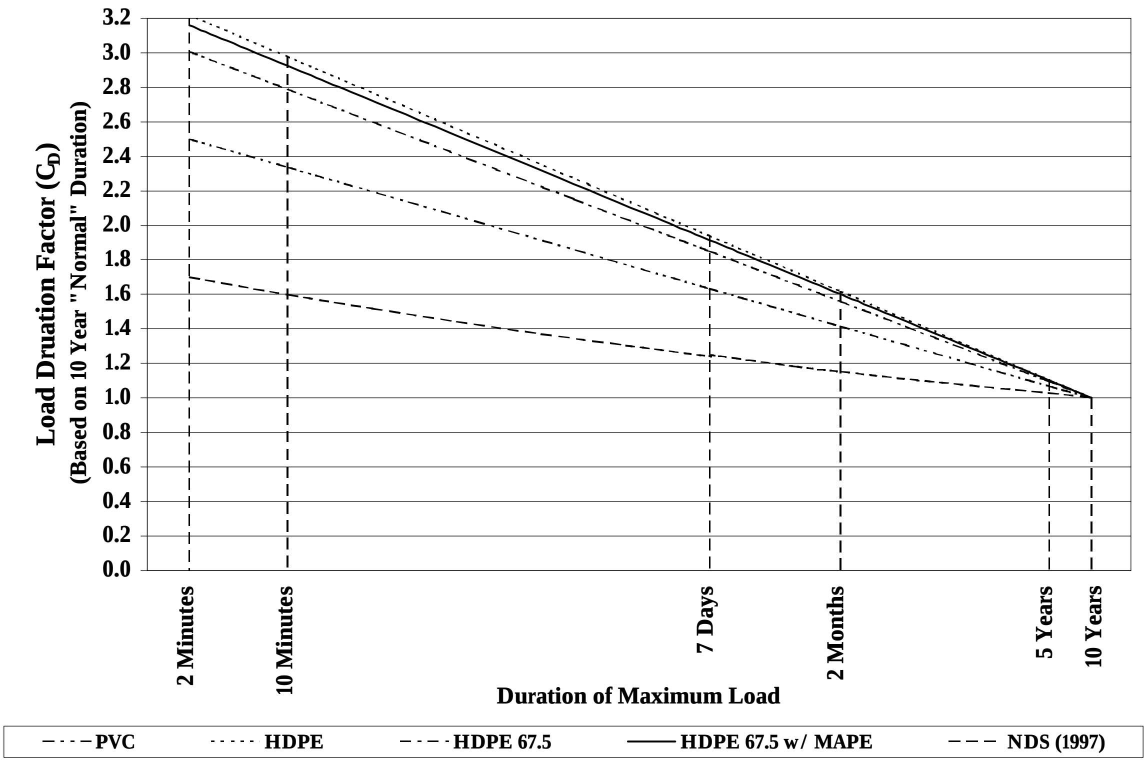

Figure 3-11: *Proposed Load-Duration Adjustment Factors*

Table 3-9: *Proposed Load-Duration Adjustment Factors (Based on a 10-Year Design Value)*

Duration	PVC	HDPE 8	HDPE 67.5	HDPE w / MAPE	Wood (NDS)
Ten Years	1.00	1.00	1.00	1.00	1.00
Five Years	1.10	1.10	1.10	1.10	1.02
Two Months	1.40	1.60	1.55	1.60	1.15
Seven Days	1.65	1.95	1.85	1.90	1.25
Ten Minutes	2.35	3.00	2.80	2.90	1.60
Two Minutes	2.50	3.20	3.00	3.15	1.70

Alternatively, it is possible to develop load-duration adjustment factors based on a shorter duration than the arbitrary ten-year duration used in the NDS. Some may be more comfortable with this approach, since the data collected is from a relatively short duration. However, using a duration shorter than ten years is merely a different means of presenting the same information because the parameters of the predictive model do not change. The use of factors based on a short duration (such as is done in LRFD for wood), however, will become increasingly non-conservative as the distance from the reference point becomes larger. It is important to note that a reliability assessment was not conducted in this analysis, but is necessary to determine the applicability of the published LRFD time-effect adjustment factors (AF&PA, 1996).

ASTM D7 EVALUATION

Previously, it was mentioned that the ASTM D7 committee was in the process of drafting a standard for evaluating the creep and load-duration performance of wood and wood-based products. The standard is currently in the balloting stage and should be released in late 2001 (Tichy 2001). A copy of the proposed standard was obtained for the purpose of comparison. The intent of the standard is to aid in the load-duration evaluation of products such as structural composite lumber and structural-use panels that exhibit load-duration behavior similar to that of solid sawn lumber. The standard outlines criteria that must be met in order to apply the load-duration adjustment factors developed for solid wood. Other products, such as WPCs, may be evaluated using the standard, but it was not designed to project the duration-of-load performance beyond the test timeframe for materials that may have mechanisms different from that of solid wood, such as WPCs (ASTM, 2001). Given this information, the WPC formulations were evaluated against the performance criteria. Differences exist between the test outlined in the standard and those performed as part of this research; however, valid comparisons can still be made. These difference include the number of specimens tested and the stress applied. The standard requires a minimum of 28 specimen, and only five were tested in this study. The standard also requires that the stress applied be 55% of the lower five-percent point estimate of static strength, while stresses tested in this study are listed in Table 3-4. The stress required by the standard was calculated for each formulation and found to lie between the two lowest stresses tested, thus data from the tests at both stress ratios will be used in the evaluation as conservative and non-conservative bounds. Table 3-10 lists the upper and lower stress ratio bounds and the calculated stress ratio required by the standard.

Table 3-10: *Stress Ratios for ASTM D7 Evaluation*

Formulation	Stress Ratio[1]		
	Lower Bound	Upper Bound	ASTM D7 Required SR
PVC	42.8%	59.9%	53.1%
HDPE 8	42.9%	60.0%	52.1%
HDPE 67.5	41.6%	58.3%	53.1%
HDPE 67.5 w/ MAPE	45.8%	64.1%	54.4%

1. Percentage of mean ultimate bending stress

Three performance criteria are used to evaluate load-duration behavior. All three must be met for product acceptance and application of NDS load-duration adjustment factors. To establish adequate strength over the 90-day duration, the standard requires that the number of failures be less than the critical order statistic of the non-parametric tolerance limit. To ensure that the material is not entering the tertiary creep phase, the creep rate must be decreasing over a minimum of three successive equally spaced time increments. Finally, to guard against excessive deformations, fractional deflection at the end of 90 days must be less than 2.0. Fractional deflection is the ratio of final deflection to deflection measured one minute after the stress is applied. Results of the evaluation are provided in Tables 3-11 through 3-13.

Table 3-11: *Adequate Strength Evaluation Results*

Formulation	Number of Failures in 90 days		
	Lower Bound	Upper Bound	ASTM D7 Requirement
PVC	0	5	0
HDPE 8	0	5	0
HDPE 67.5	0	5	0
HDPE 67.5 w/ MAPE	5	5	0

Table 3-12: *Decreasing Creep Rate Evaluation Results*

Formulation	Decreasing Creep Rate Over 90 Days		
	Lower Bound	Upper Bound[1]	ASTM D7 Requirement
PVC	No	N/A	Yes
HDPE 8	No	N/A	Yes
HDPE 67.5	No	N/A	Yes
HDPE 67.5 w/ MAPE	No	N/A	Yes

1. None of the specimen survived the required 90 days

Table 3-13: *Fractional Deflection Evaluation Results*

Formulation	Fractional Deflection		
	Lower Bound	Upper Bound[1]	ASTM D7 Requirement
PVC	1.75	1.29	< 2.0
HDPE 8	3.05	3.04	< 2.0
HDPE 67.5	3.69	3.04	< 2.0
HDPE 67.5 w/ MAPE	3.05	2.04	< 2.0

1. None of the specimen survived the required 90 days, but fractional deflections were calculated based on the deflection at failure

Examination of the values in Tables 3-11 through 3-13 indicates that three of the four formulations tested fail to meet the requirements of the draft standard based on fractional deflection at the lower bound stress ratio. The PVC formulation would need to be tested at the stress ratio required by the standard in order to determine whether or not it meets the acceptance criteria.

CONCLUSIONS

Through an experimental study of the load-duration behavior of selected WPC formulations, it was found that the PVC and HDPE 8 formulations showed a decreasing trend in creep rate over time, which would indicate the onset of a viscous secondary creep phase. However, the HDPE 67.5 and HDPE 67.5 w/ MAPE formulations did not exhibit decreasing trends in creep rate. HDPE 67.5 showed a significant increase in creep rate over the 80,000-100,000 minute range followed by a reduction in creep rate over the final interval. Of the HDPE 67.5 w/ MAPE formulations that did not fail prior to reaching the third interval, a significant increase in creep rate was also observed indicating the potential onset of a tertiary creep phase. Examination of the displacement versus time plots for the two specimens that failed during the 80,000-100,000 minute range indicates the presence of tertiary creep behavior resulting in failure. Tests conducted for longer durations and at lower stress levels may reveal the existence of secondary and/or tertiary phases for all formulations.

It was observed that the WPCs exhibited a more pronounced load-duration response than that of solid wood. This was expected because stiffness values are lower for WPCs than for solid wood. The difference is evident in the shorter times to failure for the WPC formulations at all stress levels tested.

The load-duration behavior trend of the selected WPC formulations was determined to be similar to that of solid sawn lumber, although a rotation of the exponential damage rate model (EDRM) curves was observed. When existing models used for describing the load-duration behavior of solid wood were fit to the experimental data, it was found that the EDRM developed by Gerhards (1979) provided a fit similar to the fit observed for solid wood, both visually and from examination of the standard errors of the estimates. The uncertainty surrounding the existence of a stress threshold value resulted in difficulties fitting Wood's model to the data. Inserting the stress threshold determined by Pooler (2001) as a constant into the regression analysis for HDPE 8 resulted in poorer regression statistics than when the parameter was determined through the regression analysis.

Given that the load-duration behavior trend is similar to that of solid sawn lumber, it was possible to apply the existing methodology for developing adjustment factors for load-duration effects. Load-duration factors were calculated and range from 1.0 at ten years (to be compatible with current NDS methodology) to 3.20 at two minutes. Additionally, it was found that the existing NDS load-duration adjustment factors can be conservatively applied if the WPC published bending strength were reduced by a factor determined by shifting the WPC EDRM curve to match the EDRM calibrated for Douglas-fir at the ten-year duration. However, it should be acknowledged that the load-duration response of WPCs differs enough from that of solid lumber and traditional wood composite products that efficient design and economical use of the material can only be achieved if alternative adjustment factors, such as those proposed in Table 3-9, are used.

Finally, the WPC formulations were evaluated at stress levels bracketing the stress level required in the proposed ASTM D7 standard for evaluation of load-duration behavior of structural composite lumber and structural-use panels or similar products. Although the standard does not directly apply to WPCs, an evaluation was performed nonetheless to determine if the existing load-duration adjustment factors could be applied to the selected WPCs. PVC was found to be the only formulation that could potentially meet all three performance requirements, but an experiment exactly following the provisions of the standard would have to be conducted to verify this. The three HDPE formulations failed to meet the fractional deflection requirements at a stress level below the stress level required by the standard, thus eliminating their chance to meet all three requirements at a higher stress level.

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CHAPTER FOUR

EFFECT OF LOAD RATE ON FLEXURAL PROPERTIES OF WOOD-PLASTIC COMPOSITES[1]

ABSTRACT

With the increase in wood-plastic composite (WPC) products in the commercial marketplace, it is important that the material properties of WPC products are accurately determined. Many of these products are targeted for use in flexural applications, thus the ability to accurately determine the flexural properties is of critical importance if WPC products are to compete as a structural material. Third-point bending tests were conducted on selected WPC formulations at rates ranging from 4.6 mm/min to 254 mm/min and flexural properties were determined. It was found that rate-of-load effects were present for both modulus of rupture and modulus of elasticity over certain ranges of load rate values. Specifically, significant decreases in flexural properties were observed for load rates slower than 62.5 mm/min.

INTRODUCTION

New wood-plastic composite (WPC) products are entering the marketplace at an increasing rate. Many of the applications being considered for WPC components involve flexural loading, making an accurate determination of the flexural properties of WPCs very important. Currently, no consensus standards exist for determining the flexural properties of WPCs. However, standards do exist for evaluating the flexural properties of solid wood, traditional wood composites, and plastic products.

These standards are similar in some aspects, but contain significant differences in specifying the rate-of-load application. Discretion of the WPC producers must be exercised to determine which of the existing standards, and thus which load rate, should be used. It has been documented that the rate-of-load application affects the flexural properties of solid wood (Gerhards, 1986; Spencer, 1979), and that changes in strain rate affect the yield stress of plastics (Hobeika et al., 2000). It is, however, unknown whether rate-of-load effects exist in WPCs, and if present, the magnitude of the effect is unknown. It was the intent of this experimental research investigation to determine the influence of the rate-of-load application on the flexural response of wood-plastic composites.

BACKGROUND

The standard for determining the flexural properties of structural-sized wood members was created in 1924 when ASTM D198 was first published. The standard recommends that a load rate should be chosen to achieve failure in about 10 minutes with a minimum of 6 minutes and a maximum of 20 minutes. A constant rate of outer fiber strain equal to 0.001 mm/mm/min is suggested as being sufficient to produce failure within the required timeframe (ASTM, 1998).

Similar standards exist for evaluating the flexural properties of plastic products. ASTM D6109 (1997) is a standard test method for determining the flexural properties of unreinforced and reinforced plastic lumber of rectangular or square cross-sections. The standard specifies that it is a test method for evaluating plastic lumber as a product, but is not a material property test method (ASTM, 1997). Two methods are presented, one for

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[1] To be submitted for review and possible publication in *Wood and Fiber Science*, Society for Wood Science and Technology.

products used in the flatwise, weak, or “plank” orientation, and one for products used in the edgewise, strong, or “joist” orientation. The method for edgewise testing specifies that the load rate must be based on a constant rate of outer-fiber strain. A range of 0.002 to 0.003 mm/mm/min is specified for the rate of outer-fiber strain to be used to calculate the rate of crosshead motion. The equation supplied for use in calculating the rate of crosshead motion is given in Equation 4-1:

$$R = \frac{0.185ZL^2}{d} \qquad (4\text{-}1)$$

where R is the rate of crosshead motion, Z is the rate of outer-fiber strain, L is the support span, and d is the specimen depth.

Another standard for determining the flexural properties of plastic products is ASTM D790 (1997), a standard test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. Again, two methods are presented, one for materials that break at comparatively small deflections, and one for materials that undergo large deflections during testing. The first method specifies a load rate based on the outer fiber strain rate of 0.01 mm/mm/min. The standard provides an equation to calculate the rate of crosshead motion and is given in Equation 4-2 :

$$R = \frac{ZL^2}{6d} \qquad (4\text{-}2)$$

where all parameters are as defined previously.

Haiar (2000) recommended test procedures for determining material properties of both polyvinyl chloride (PVC) and high-density polyethylene (HDPE) wood-plastic composite formulations. To establish flexural properties, Haiar recommended that the method, apparatus, and procedures outlined in ASTM D198 be followed with two modifications: the load rate is to be taken from ASTM D790, and the span shall be determined from the ratio of length to radius of gyration. The load rate modification was made to account for potential creep effects that may be present at slower rates, and the span modification was made to allow for hollow or non-rectangular sections.

The stress-strain relationship of WPCs is typically non-linear, creating difficulties in accurately determining the modulus of elasticity. Hermanson et al. (1998) explored the use of a four-parameter hyperbolic tangent constitutive relationship previously shown to fit the load-displacement relationship of WPCs. They found that a simplified two-parameter variation of the model still provided an accurate representation of WPC behavior. In terms of the stress-strain relationship, the simplified equation has the form:

$$s = c_1 \mathrm{Tanh}\,(c_2 e) \qquad (4\text{-}3)$$

where σ is stress, Tanh is the hyperbolic tangent function, ε is the strain, and c_1 and c_2 are constants determined through a least squares method. Hermanson et al. (1998) also found that Equation 4-4 could be used to estimate the initial modulus of elasticity:

$$E = c_1 c_2 \qquad (4\text{-}4)$$

where E is the modulus of elasticity, and all other parameters are as defined previously. It was determined that Equation 4-4 over predicts a linear estimate by 5-10% at a prescribed 1% strain.

Very little documentation exists detailing research conducted to investigate the effect of rate-of-load application on the flexural properties of WPC products. Thus, experimental research is necessary to determine if rate-of-load effects exist for WPC products and to evaluate the two standards currently being used to determine the flexural properties of WPC products.

MATERIALS

Four wood-plastic composite formulations were selected for evaluation. The first formulation was produced with polyvinyl chloride (PVC) and the remaining three were produced with high-density polyethylene (HDPE). The HDPE 8 formulation contained the following processing aides: 2% zinc stearate (Ferro Chemicals Synpro DLG-20B) and 1% EBS wax (GE Specialty). Another of the HDPE formulations contained an ethylene-maleic anhydride polymer (MAPE), which is a commercially available coupling agent added to strengthen the bond at the interface between the polyethylene and wood fibers. Table 4-1 provides the material composition of each formulation and gives the percentage used by weight.

Table 4-1: *Formulation Materials and Percentages*

Formulation	% Flour	Wood Flour Type	% Plastic	Plastic Type	Additives
PVC	50	Ponderosa Pine (AWF #4020)	50	PVC Compound (Georgia Gulf) (3014 nat 00)	None
HDPE 8	58	Maple (AWF #4010)	31	HDPE (Equistar) (LB 0100 00)	8% Ceramic Talc (Suzqrite) 3% Processing Aides
HDPE 67.5	67.5	Maple (AWF #4010)	32.5	HDPE (Equistar) (LB 0100 00)	None
HDPE 67.5 w/ MAPE	67.5	Maple (AWF #4010)	30.95	HDPE (Equistar) (LB 0100 00)	1.55% MAPE (AlliedSignal) (575A1)

All materials were dry blended in a 1.2-m (4-ft) diameter drum mixer in 20-kg (44-lb) batches. The dry mixture was then loaded into the hopper a conical counter-rotating twin screw extruder (Cincinnati-Milacron E55) and a two-box cross section was extruded using a stranding die (Laver, 1996) and cut into 2.44-m (8-ft) lengths. Process temperatures are provided in Table 4-2.

Table 4-2: *Extrusion Process Temperatures*

Formulation	Process Temperature (^{o}C)				
	Barrel	Screw	Die Zone 1	Die Zone 2	Die Zone 3
PVC	168	140	174	174	160
HDPE 8	163	163	171	171	171
HDPE 67.5	163	163	163	171	143
HDPE 67.5 w/ MAPE	163	163	163	171	143

Figure 4-1 illustrates the two-box cross section and Table 4-3 summarizes the nominal section dimensions and selected properties.

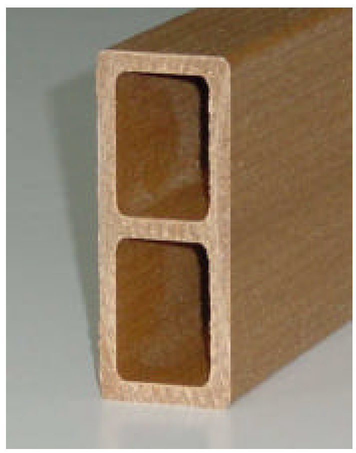

Figure 4-1: *Two-Box Cross Section*

Table 4-3: *Nominal Two-Box Section Dimensions and Properties*

Property	Value
Depth	89 mm (3.5 in.)
Width	36 mm (1.40 in.)
Wall Thickness	5 mm (0.20 in.)
Cross-Sectional Area	1290 mm^2 (2.00 in.^{2})
Moment of Inertia (Strong Axis)	1.05x10^6 mm^4 (2.52 in.^{4})

LOAD RATE TESTS

Five specimens from each formulation were weighed to the nearest milligram on a digital scale and cross-sectional dimensions were measured to the nearest 0.025 mm (0.001 in.) with digital calipers. Procedures outlined by Haiar (2000) for determining strong-axis modulus of rupture (MOR) for structural wood-plastic composite beams were followed. The test method specifies that ASTM D198 (1998), a standard test method for determining properties of structural lumber, be followed with two exceptions: load rate and span length. Haiar recommended that the load rate be calculated according to ASTM D790 (1997), a standard test method for determining flexural properties of unreinforced and reinforced plastics. The standard specifies that the load be applied such that the rate of strain in the outer fiber is 0.01 mm/mm/min. (0.01 in./in./min.). Based on nominal section dimensions, this corresponded to a load rate of 62.5 mm/min. (2.46 in./min.). This "standard" load rate and the other rates selected are listed in Table 4-4 along with the corresponding outer-fiber strain rate.

Table 4-4: *Load Rates Tested and Corresponding Strain Rates*

Rate-of-Load Application mm/min (in./min)	Rate-of-Strain in Outer Fiber mm/mm/min (in./in./min)
4.6 (0.18)	0.0007 (0.0007)
62.5 (2.46)	0.01 (0.01)
254 (10)	0.04 (0.04)

Haiar (2000) recommended that the ratio of support span length to radius of gyration be used to determine the test span; however, a span consistent with that used in static bending tests performed as part of the load-duration research (see Chapter Three) of 1.83 m (6 ft), was used. Similarly, the load was applied at third points, or 610 mm (24 in.) from the end reactions to be consistent with the previous work. Lateral bracing was provided along the span to ensure that lateral-torsional buckling effects were negligible.

Five specimens from each formulation were ramp loaded to failure at the rates listed in Table 4-4 using a computer-controlled screw-driven 146 N (33 k) Instron 4400R testing machine. A spreader beam was used to evenly distribute the single point load of the crosshead into two point loads applied to the specimen. Center span displacement was measured using a linear position transducer accurate to +/- 1.27 mm (0.05 in.). A computerized data acquisition system recorded load-displacement data, maximum load, and time-to-failure for each specimen. The test setup is shown in Figure 4-2.

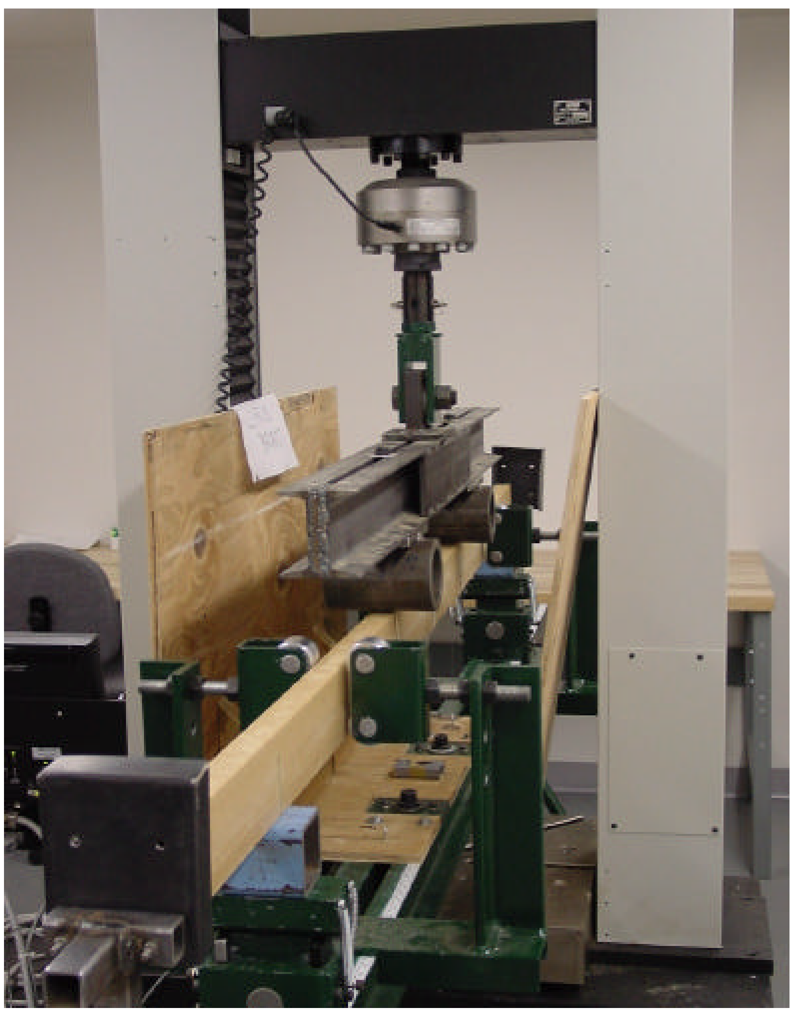

Figure 4-2: *Load-Rate Test Setup*

RESULTS

The objective of this research was to evaluate the effects of load rate on flexural properties, specifically the MOR and modulus of elasticity (MOE). Deflection at failure was also monitored and recorded. A load versus displacement curve was generated for each specimen tested. Figures 4-3 through 4-6 illustrate a typical load-displacement curve for each formulation at the "standard" 62.5 mm/min rate of loading. (Note: The remaining load-displacement curves can be found in Appendix C). Examination of Figs. 4-3 through 4-6 reveals that the PVC and HDPE 67.5 w/ MAPE formulations exhibited less ductility than the HDPE 8 and HDPE 67.5 formulations.

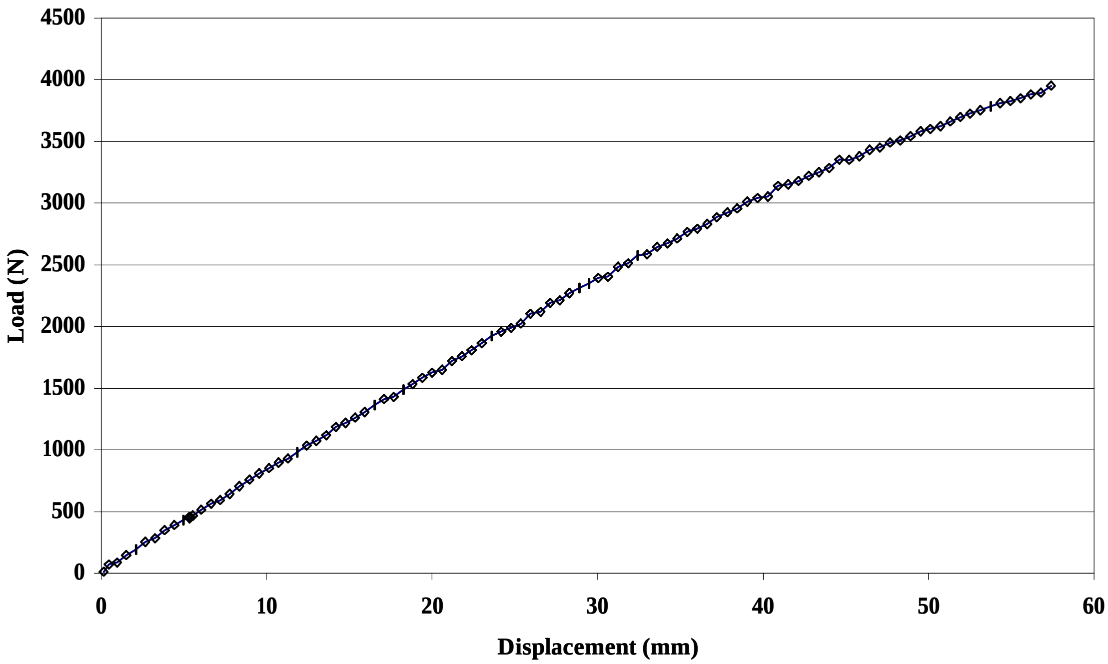

Figure 4-3: *Load versus Displacement for PVC at 62.5 mm/min*

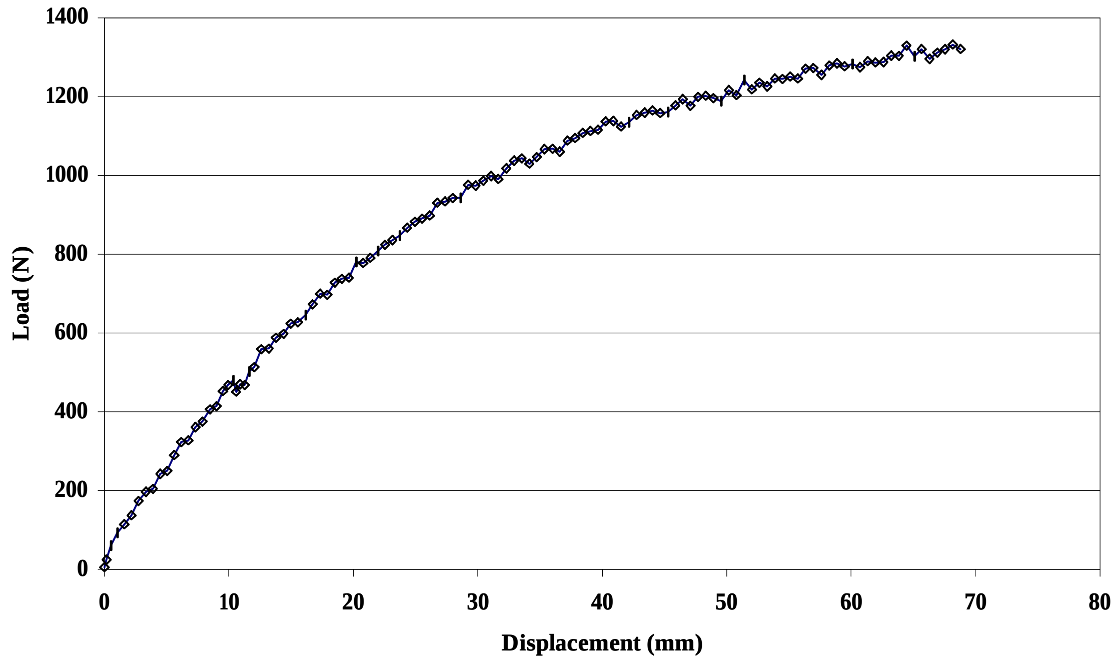

Figure 4-4: *Load versus Displacement for HDPE 8 at 62.5 mm/min*

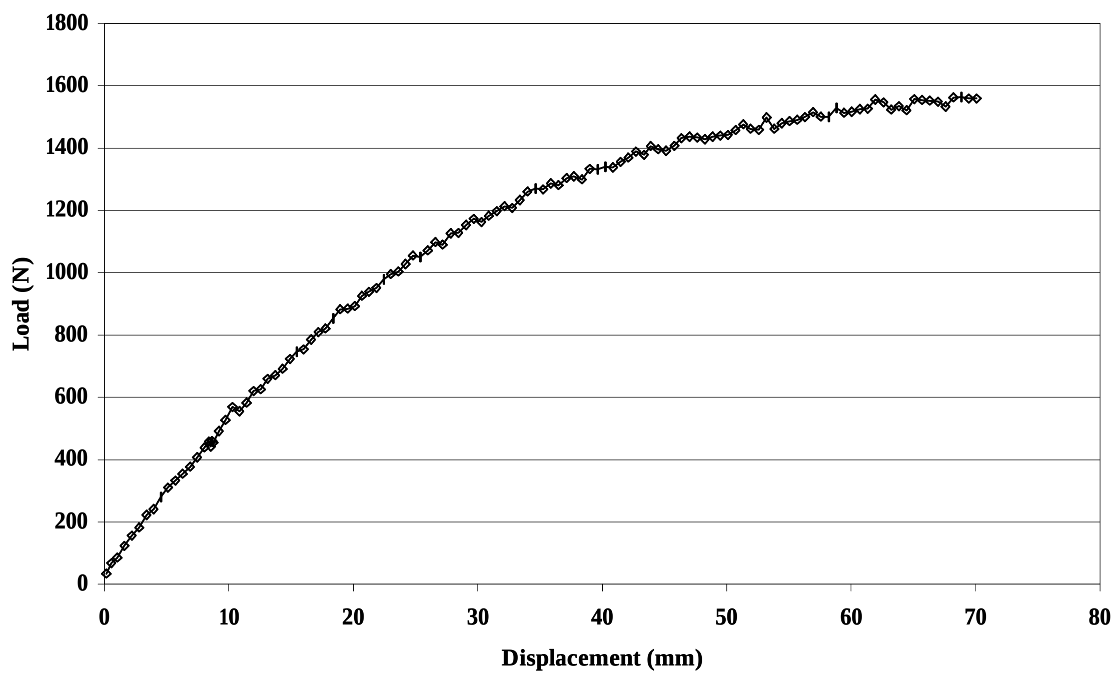

Figure 4-5: *Load versus Displacement for HDPE 67.5 at 62.5 mm/min*

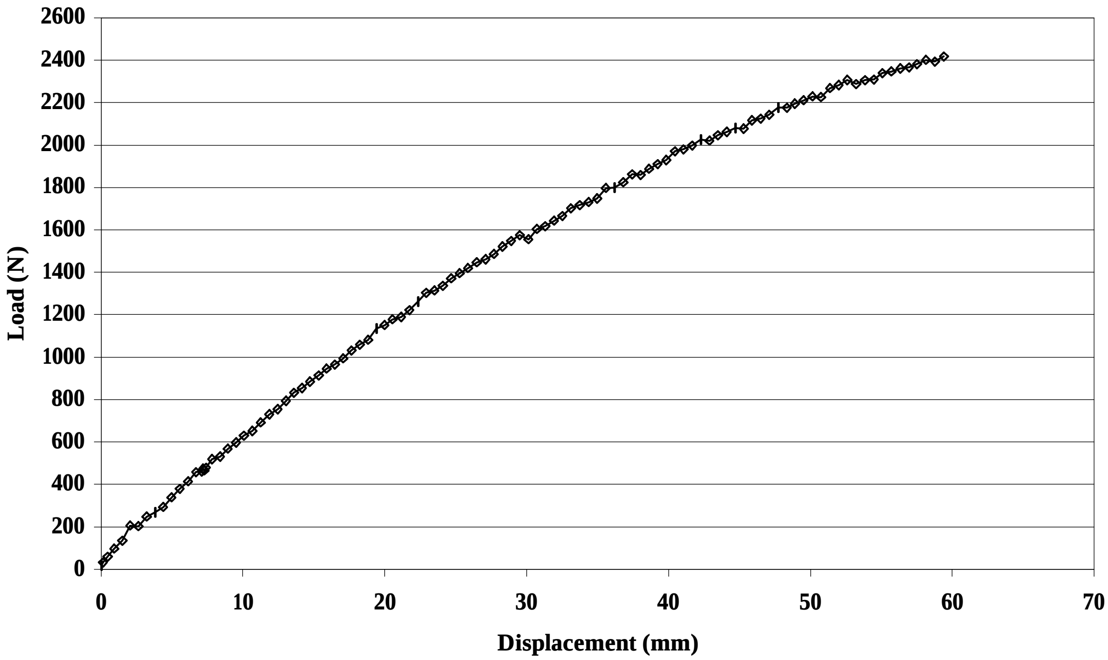

Figure 4-6: *Load versus Displacement for HDPE 67.5 w/ MAPE at 62.5 mm/min*

Using the load at failure data, MOR values were calculated for each specimen. The average MOR values at each rate of loading are presented in Table 4-5 and in Fig. 4-7. From a visual inspection, it appears that MOR increased with the increase in rate of load application from 4.6 to 62.5 mm/min and then remained nearly constant between 62.5 mm/min and 254 mm/min for all four formulations.

Table 4-5: *Modulus of Rupture Values*

Formulation	Modulus of Rupture (MPa)		
	4.6 mm/min	62.5 mm/ min	254 mm/min
PVC	42.55	48.29	47.48
HDPE 8	14.56	16.88	17.68
HDPE 67.5	18.15	21.13	21.04
HDPE 67.5 w/ MAPE	27.63	32.03	33.23

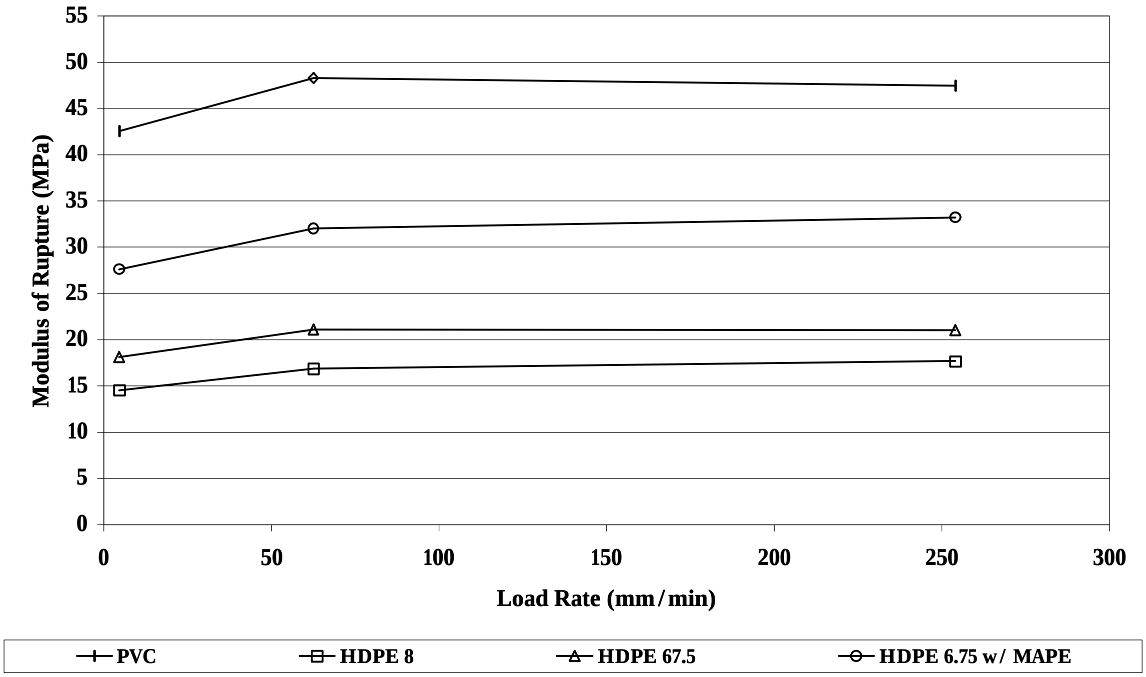

Figure 4-7: *Rate-of-Load Effect on Modulus of Rupture*

To confirm the trends observed for the average values, a one-sided t test was performed at the 0.05 significance level to determine whether statistical differences in mean values exist. Analysis of separate, larger data sets confirmed that the normally distributed data assumption is not violated for any of the formulations. The MOR values from the 62.5 mm/min (ASTM D790) load rate were used as the standard to which the MOR values from the 4.6 mm/min and 254 mm/min rates were compared. Table 4-6 presents the results for each formulation.

Table 4-6: *t Test Results for MOR Values*

Load Rate	t Statistic	t Critical	P-Value
PVC			
4.6 mm/min to 62.5 mm/min	7.663	1.860	2.973E-05
62.5 mm/min to 254 mm/min	0.971	1.860	0.180
HDPE 8			
4.6 mm/min to 62.5 mm/min	6.701	1.860	7.628E-05
62.5 mm/min to 254 mm/min	2.418	1.860	0.021
HDPE 67.5			
4.6 mm/min to 62.5 mm/min	9.437	1.860	6.529E-06
62.5 mm/min to 254 mm/min	0.159	1.860	0.439
HDPE 67.5 w/ MAPE			
4.6 mm/min to 62.5 mm/min	27.704	1.860	1.555E-09
62.5 mm/min to 254 mm/min	7.622	1.860	3.089E-05

The t test results for the modulus of rupture do not fully agree with the visual observations made for the data. The MOR at a load rate slower than the ASTM D790 rate was found to be statistically different from the MOR at the ASTM D790 rate for all formulations. The MOR at a load rate faster than the ASTM D790 rate was found to be statistically similar to the MOR at the ASTM D790 rate for the PVC and HDPE 67.5 formulations and statistically different for the HDPE 8 and HDPE 67.5 w/ MAPE formulations.

For the HDPE based formulations, a trend toward a linear increase in modulus of rupture values with the logarithm of loading rate was observed, however the same was not true for the PVC formulation. Gerhards and Link (1986) observed a similar trend in strength values of solid sawn lumber. With a limited number of data points collected over a broad range of load rates, it was not possible here to explore the relationship between the two beyond the point of making a note of the potential trend.

Following Hermanson et al. (1998), the method of least squares was used to estimate parameters c_1 and c_2 in Equation 4-3, and then the hyperbolic tangent modulus of elasticity was calculated for each specimen using Equation 4-4. Table 4-7 contains the mean values of c_1 (kPa) and c_2 (unitless) for each formulation and rate-of-load.

Table 4-7: *Mean Values of Constants for Hyperbolic Tangent Relationship*

Formulation	4.6 mm/min		62.5 mm/min		254 mm/min	
	c_1	c_2	c_1	c_2	c_1	c_2
PVC	60655	143	74407	114	76832	115
HDPE 8	14400	240	16920	258	17961	265
HDPE 67.5	17726	266	21128	255	21606	279
HDPE 67.5 w/ MAPE	28986	188	37232	168	38670	181

Additionally, an initial tangent modulus of elasticity was calculated for comparison by assuming that the stress-strain relationship was linear in the range from 0-30% of the ultimate stress. Table 4-8 and Table 4-9 contain average values for hyperbolic tangent MOE and initial tangent MOE for each specimen, respectively. Figures 4-8 and 4-9 present the data in graphical form for convenience. Note that the values in Tables 4-7 and 4-8 are both mean values, and that the constants c_1 and c_2 are not perfectly correlated. Therefore, the values in Table 4-8 cannot be obtained by direct multiplication of the values in Table 4-7 because the average of the products does not equal the product of the averages for non-perfectly correlated values.

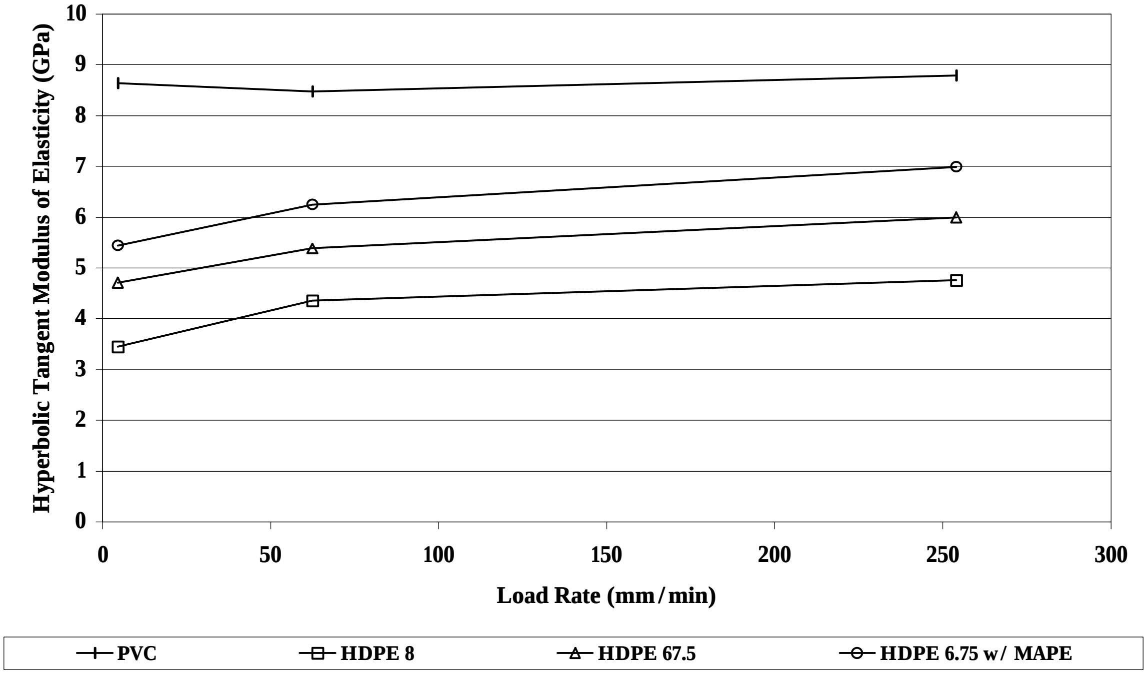

Figure 4-8: *Rate-of-Load Effect on Hyperbolic Tangent Modulus of Elasticity*

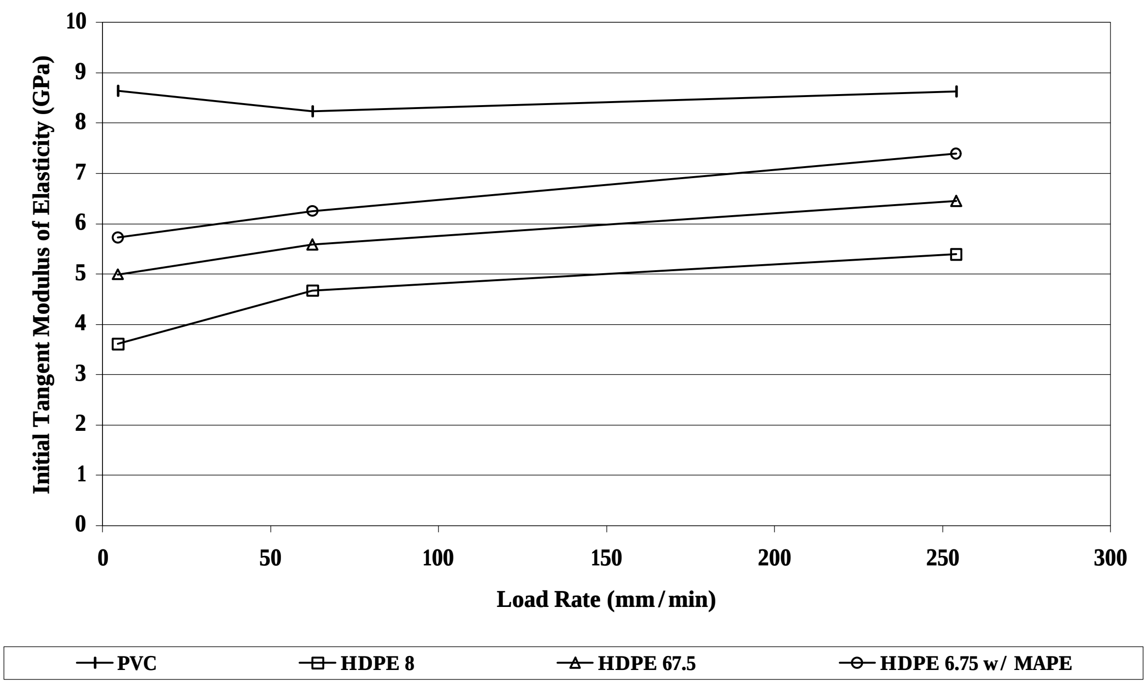

Figure 4-9: *Rate-of-Load Effect on Initial Tangent Modulus of Elasticity*

Table 4-8: *Hyperbolic Tangent Modulus of ElasticityValues*

Formulation	Hyperbolic Tangent Modulus of Elasticity (GPa)		
	4.6 mm/min	62.5 mm/ min	254 mm/min
PVC	8.84	8.48	8.80
HDPE 8	3.42	4.36	4.76
HDPE 67.5	4.72	5.39	6.00
HDPE 67.5 w/ MAPE	5.45	6.25	7.00

Table 4-9: *Initial Tangent Modulus of Elasticity Values*

Formulation	Initial Tangent Modulus of Elasticity (GPa)		
	4.6 mm/min	62.5 mm/ min	254 mm/min
PVC	8.92	8.23	8.63
HDPE 8	3.59	4.67	5.39
HDPE 67.5	4.99	5.58	6.45
HDPE 67.5 w/ MAPE	5.72	6.25	7.39

A comparison of the values in Tables 4-8 and 4-9 shows that, in general, the initial tangent modulus values are an average of 4.9% higher than those calculated following the method proposed by Hermanson et al. (1998). However, the hyperbolic tangent constitutive relationship is considered to give a more reliable and consistent representation of the behavior of WPC materials. Therefore the hyperbolic tangent MOE will be assumed representative of the material and, from this point forward, any use of the term MOE refers to the hyperbolic tangent MOE.

Figure 4-9 indicates that MOE values increase with an increase in load rate for all three HDPE-based formulations, and that MOE values for PVC remain nearly constant after decreasing slightly at first. Again, a one-sided t test was performed at the 0.05 significance level to determine whether statistical differences in mean values exist. The MOE values from the 62.5 mm/min (ASTM D790) load rate were used as the standard to which the MOE values from the 4.6 mm/min and 254 mm/min rates were compared. Table 4-10 presents the results for each formulation. It was found that as the rate-of-load increases, the effect of viscous flow of the material is decreased, thus the increase in MOE values was expected.

Table 4-10: *t Test Results for MOE Values*

Load Rate	t Statistic	t Critical	P-Value
PVC			
4.6 mm/min to 62.5 mm/min	1.242	1.860	0.125
62.5 mm/min to 254 mm/min	3.078	1.860	0.008
HDPE 8			
4.6 mm/min to 62.5 mm/min	8.244	1.860	1.758E-05
62.5 mm/min to 254 mm/min	4.372	1.860	0.001
HDPE 67.5			
4.6 mm/min to 62.5 mm/min	7.919	1.860	2.349E-05
62.5 mm/min to 254 mm/min	3.950	1.860	0.002
HDPE 67.5 w/ MAPE			
4.6 mm/min to 62.5 mm/min	8.443	1.860	1.478E-05
62.5 mm/min to 254 mm/min	4.669	1.860	8.024E-04

The t test results for the modulus of elasticity confirm the visual observations made for the data for all formulations tested with a few exceptions. The MOE at a load rate slower than the ASTM D790 rate was found to be statistically different from the MOE at the ASTM D790 rate for all HDPE formulations, while the MOE was found to be statistically similar for the PVC formulation. The MOE at a load rate faster than the ASTM D790 rate was found to be statistically different from the MOE at the ASTM D790 rate for all formulations.

Finally, deflection at failure was evaluated in a manner similar to that done for MOR and MOE to further investigate the effects of rate-of-load application. A complete analysis of the deflection data can be found in Appendix E. Figure 4-10 illustrates a decreasing trend in deflection as rate-of-load application increases. T test results (see Appendix E) confirm that a rate-of-load effect is present for deflection at failure values over the 4.6 mm/min to 62.5 mm/min interval for all formulations, and a rate-of-load effect is present for deflection at failure values over the 62.5 mm/min to 254 mm/min interval for all formulations except HDPE 8. Again, it was found that as the rate-of-load increases, the effect of viscous flow of the material is decreased, thus the decrease in deflection at failure was expected.

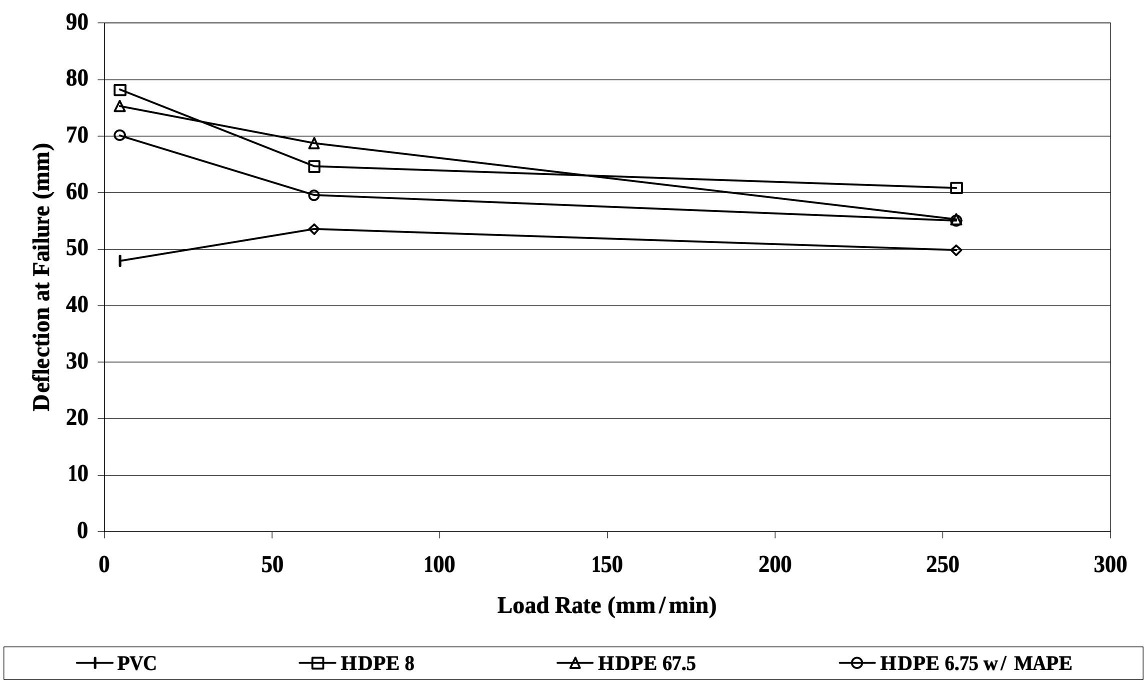

Figure 4-10: *Rate-of-Load Effect on Deflection at Failure*

CONCLUSIONS

Through an experimental evaluation of the effect that rate-of-load application has on flexural properties of selected wood-plastic composites, it was determined that rate-of-load effects occur only over certain ranges of load rate application. A one-sided t test was used to determine if modulus of rupture and modulus of elasticity values were dependent on rate-of-load application. An increase in rate-of-load application, from 4.6 mm/min (approximately one-third the rate specified in ASTM D6109 (1997)) to 62.5 mm/min (the rate specified in Procedure A of ASTM D790 (1997)), resulted in an increase in MOR values for all formulations. Similarly, an increase was noticed in MOE values for all formulations except PVC, for which values remained statistically unchanged. A further increase in rate-of-load application, from 62.5 m/min to 254 mm/min, resulted in an increase in MOR values for both HDPE 8 and HDPE 67.5 w/ MAPE, while the MOR values for PVC and HDPE 67.5 remained similar. MOE values were found to increase over the 62.5 mm/min to 254 mm/min interval for all formulations.

It is concluded from the results presented herein that a rate-of-load effect is present in flexural response of WPCs, and that there is a significant difference between the properties obtained from the load rates specified by the two ASTM standards currently used. At approximately one-third the load rate calculated according to ASTM D6109 (1997), average MOR values were found to be between 13% and 15% lower than at the ASTM D790 (1997) rate, and average MOE values were between 2% and 23% lower. Without having the exact relationship between load rate and MOR or MOE, it is difficult to determine the magnitude of the difference that would be observed using the ASTM D6109 rate. However, if a linear relationship were assumed, the percent difference would remain at approximately 13% for MOR, and between 2% and 21% for MOE. Consequently, it is quite apparent that the potential for underestimating the flexural properties of WPC products exists.

An examination of load rates above the ASTM D790 rate shows that, at four times the load rate specified in ASTM D790, average MOR values were either constant, or increased by less than 5% depending on the formulation, and average MOE values increased by between 4% and 11%. While a general increase in flexural properties was witnessed at the 254 mm/min load rate, the short duration of the test, 13 seconds on average, makes high-speed data acquisition (5 Hz or greater) necessary in order to collect an adequate amount of data. Thus, it is concluded that flexural tests conducted at the ASTM D790 recommended outer-fiber strain rate of 0.01 mm/mm/min are not only practical in terms of the test equipment required, but also produce representative material properties. The values obtained using this load rate were conservative when compared to those obtained using a higher rate of outer fiber strain, but not overly conservative as was observed using a lower rate of outer-fiber strain. Furthermore, ASTM D6109, while admittedly not a material property test standard, should not be used for determining the rate of load used in flexural tests of wood-plastic composites, as the outer-fiber strain rates that it recommends results in overly conservative estimates of both modulus of rupture and modulus of elasticity.

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CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

Conclusions drawn from the research presented herein are presented in two sections: (1) those pertaining to the load-duration behavior of wood-plastic composites, and (2) those pertaining to rate-of-load effects in wood-plastic composites. Recommendations for future studies are provided following the conclusion sections.

LOAD-DURATION CONCLUSIONS

Through an experimental study of the load-duration behavior of selected WPC formulations, it was found that the PVC and HDPE 8 formulations showed a decreasing trend in creep rate over time, which would indicate the onset of a viscous secondary creep phase. However, the HDPE 67.5 and HDPE 67.5 w/ MAPE formulations did not exhibit decreasing trends in creep rate. HDPE 67.5 showed a significant increase in creep rate over the 80,000-100,000 minute range followed by a reduction in creep rate over the final interval. Of the HDPE 67.5 w/ MAPE formulations that did not fail prior to reaching the third interval, a significant increase in creep rate was also observed indicating the potential onset of a tertiary creep phase. Examination of the displacement versus time plots for the two specimens that failed during the 80,000-100,000 minute range indicates the presence of tertiary creep behavior resulting in failure. Tests conducted for longer durations and at lower stress levels may reveal the existence of secondary and/or tertiary phases for all formulations.

It was observed that the WPCs exhibited a more pronounced load-duration response than that of solid wood. This was expected because stiffness values are lower for WPCs than for solid wood. The difference is evident in the shorter times to failure for the WPC formulations at all stress levels tested.

The load-duration behavior trend of the selected WPC formulations was determined to be similar to that of solid sawn lumber, although a rotation of the exponential damage rate model (EDRM) curves was observed. When existing models used for describing the load-duration behavior of solid wood were fit to the experimental data, it was found that the EDRM developed by Gerhards (1979) provided a fit similar to the fit observed for solid wood, both visually and from examination of the standard errors of the estimates. The uncertainty surrounding the existence of a stress threshold value resulted in difficulties fitting Wood's model to the data. The model fit did not improve when the stress threshold determined by Pooler (2001) for the HDPE 8 formulation was used in the regression analysis.

Given that the load-duration behavior trend is similar to that of solid sawn lumber, it was possible to apply the existing methodology for developing adjustment factors for load-duration effects. Load-duration factors were calculated and range from 1.0 at ten years (to be compatible with current NDS methodology) to 3.20 at two minutes. Additionally, it was found that the existing NDS load-duration adjustment factors can be conservatively applied if the WPC published bending strength were reduced by a factor determined by shifting the WPC EDRM curve to match the EDRM calibrated for Douglas-fir at the ten-year duration. However, it should be acknowledged that the load-duration response of WPCs differs enough from that of solid lumber and traditional wood composite products that efficient design and economical use of the material can only be achieved if alternative adjustment factors, such as those proposed in Table 3-9, are used.

Finally, the formulations were evaluated based on the proposed ASTM D7 standard for evaluation of load-duration behavior of structural composite lumber and structural-use panels or similar products. Although the standard does not directly apply to WPCs, an evaluation was performed nonetheless to determine if the existing load-duration adjustment factors could be applied to the selected WPCs. PVC was found to be the only formulation that could potentially meet all three performance requirements, but an experiment exactly following the provisions of the standard would have to be conducted to verify this. The other three formulations failed to meet the fractional deflection requirements at a stress level below the stress level required by the standard, thus eliminating their chance to meet all three requirements at a higher stress level.

RATE-OF-LOAD CONCLUSIONS

Through an experimental evaluation of the effect that the rate-of-load application has on flexural properties of selected wood-plastic composites, it was determined that rate-of-load effects occur only over certain ranges of load rate application. A one-sided t test at the 0.05 significance level was used on both modulus of rupture and modulus of elasticity values to determine whether rate-of-load effects were present. An increase in rate-of-load application, from 4.6 mm/min (approximately one-third the rate specified in ASTM D6109 (1997)) to 62.5 mm/min (the rate specified in Procedure A of ASTM D790 (1997)), resulted in an increase in MOR values for all formulations. Similarly, an increase was noticed in MOE values for all formulations except PVC, for which values remained constant. A further increase in rate-of-load application, from 62.5 m/min to 254 mm/min, resulted in an increase in MOR values for both HDPE 8 and HDPE 67.5 w/

MAPE, while the MOR values for PVC and HDPE 67.5 remained constant. MOE values for all formulations were found to increase over this range of load rates.

It is concluded from the results presented herein that a rate-of-load effect is present in flexural response of WPCs, and that there is a significant difference between the properties obtained from the load rates specified by the two ASTM standards currently used. At approximately one-third the load rate calculated according to ASTM D6109 (1997), average MOR values were found to be between 13% and 15% lower than at the ASTM D790 (1997) rate, and average MOE values were between 2% and 23% lower. Without having the exact relationship between load rate and MOR or MOE, it is difficult to determine the magnitude of the difference that would be observed using the ASTM D6109 rate. However, if a linear relationship were assumed, the percent difference would remain at approximately 13% for MOR, and between 2% and 21% for MOE. Consequently, it is quite apparent that the potential for underestimating the flexural properties of WPC products exists.

An examination of load rates above the ASTM D790 rate shows that, at four times the load rate specified in ASTM D790, average MOR values were either constant, or increased by less than 5% depending on the formulation, and average MOE values increased by between 4% and 11%. While a general increase in flexural properties was witnessed at the 254 mm/min load rate, the short duration of the test, 13 seconds on average, makes high-speed data acquisition (5 Hz or greater) necessary in order to collect an adequate amount of data. Thus, it is concluded that flexural tests conducted at the ASTM D790 recommended outer-fiber strain rate of 0.01 mm/mm/min are not only practical in terms of the test equipment required, but also produce representative material properties. The values obtained using this load rate were conservative when compared to those obtained using a higher rate of outer fiber strain, but not overly conservative as was observed using a lower rate of outer-fiber strain. Further, ASTM D6109, while admittedly not a material property test standard, should not be used for determining the rate of load used in flexural tests of wood-plastic composites, as the outer-fiber strain rates that it recommends results in overly conservative estimates of both modulus of rupture and modulus of elasticity.

RECOMMENDATIONS

The experimental work and results presented in this thesis were only the beginning of the research that must be conducted on WPC products if we wish to understand their load-duration behavior. While the 90-day test period is convenient for obtaining results in a relatively short period of time, it is inadequate for accurately determining the longer-term load-duration behavior of the materials. Tests over a wider range of stress levels conducted for a minimum of one year are recommended to help characterize the load-duration behavior of WPCs. Specifically, long-term tests at stress ratios between 50% and 20% are recommended to determine whether a stress threshold exists. Removing the uncertainty surrounding the existence of a stress threshold will allow the selection of the most representative predictive model and in turn will result in the development of more accurate load-duration adjustment factors.

All of the load-duration experimental work was conducted at or near a temperature of 21° C (70° F). It is known that WPC products are subject to temperature effects in static testing of flexural strength, which indicates that a temperature effect may be present for time-dependent strength as well. Thus, load-duration tests conducted over a range of temperatures are recommended to determine if a load-duration temperature adjustment factor is necessary as well.

Finally, the problems associated with the lack of standardized procedures for determining static flexural strength and load-duration behavior must be addressed immediately. The many differences between the formulations that are, or will become, commercially available requires that strict guidelines be in place for product acceptance if consumer confidence in WPC products is desired. Variations in temperature or rate-of-load application can significantly impact the experimental results and create the potential for misrepresentation of product performance.

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APPENDIX A

DAMAGE ACCUMULATION MODEL DERIVATIONS

INTRODUCTION

The linear damage accumulation theory is based on the concept that a certain stress, when applied to a member, causes unrecoverable damage. This damage accumulates with repeated application of the initial stress or with application of other stress levels. The damage can be summed over multiple load histories to determine the total amount of damage present. Once this accumulated damage reaches a sufficient level, failure of the member occurs. The summation of damage can be expressed as:

$$a = \sum_{i=1}^{n} \frac{t_i}{(t_f)_i}$$

where α is a state variable representing damage that ranges from zero, meaning no damage occurs, to one, meaning failure occurs; t_i is the duration of loading at a specific stress level σ_i, and $(t_f)_i$ is the duration-of-load required to cause failure at the σ_i stress level. Alternatively, the summation of damage can be written in integral form:

$$a = \int_0^t \frac{dt}{t_f}$$

Many damage models express the rate at which damage accumulates over time as a function the applied stress:

$$\frac{da}{dt} = f(s)$$

GERHARDS' EDRM

The exponential damage rate model developed by Gerhards (1979) expresses the rate of damage accumulation as follows:

$$\frac{da}{dt} = \exp(-A + Bs)$$

where A and B are model constants and σ is the ratio of applied stress to the short-term strength. The model can be manipulated, as follows, to achieve an equation for time-to-failure, which is of interest in characterizing load-duration performance.

Rearrange and integrate:

$$\int da = \int \exp(-A + Bs)\, dt$$

$$a = t \cdot \exp(-A + Bs)$$

To achieve an equation for time-to-failure, failure must occur. Thus, α must equal 1, and t becomes t_f.

$$1 = t_f \cdot \exp(-A + Bs)$$

Solving for t_f yields:

$$t_f = \frac{1}{\exp(-A + Bs)} \quad \text{or} \quad t_f = \exp(A - Bs)$$

Model constants A and B can be determined with linear regression by manipulation of the equation:

$$LN(t_f) = A - Bs$$

where elements of a linear equation, y = mx + b, are defined as: y = LN(t_f), m = B, and b = A.

WOOD'S MODEL (MADISON CURVE)

The hyperbolic model developed by Wood (1951), commonly known as the Madison curve, can be expressed as a damage accumulation model as well. The rate of damage accumulation has the following form:

$$\frac{da}{dt} = A(s - s_0)^B$$

where A and B are model constants, σ is the ratio of applied stress to the short-term strength, and σ_0 is a stress threshold below which no damage occurs. The model can be manipulated, as follows, to achieve an equation for time-to-failure, which is of interest in characterizing load-duration performance.

Rearrange and integrate:

$$\int da = \int A(s - s_0)^B \, dt$$

$$a = t \cdot A(s - s_0)^B$$

Again, to achieve an equation for time-to-failure, failure must occur. Thus, α must equal 1, and t becomes t_f.

$$1 = t_f \cdot A(s - s_0)^B$$

Solving for t_f yields:

$$t_f = \frac{1}{A(s - s_0)^B} \quad \text{or} \quad t_f = A(s - s_0)^B$$

Model constants A, B and σ_0 must be determined through non-linear regression.

REFERENCES

Gerhards, C. C. (1979). "Time-related effects on wood strength: a linear-cumulative damage theory." *Wood Science*, 11(3), 139-144.

Wood, L. W. (1951). "Relation of strength of wood to duration-of-load." *Report No. 1916*, U.S.D.A Forest Service, Forest Products Laboratory, Madison, WI.

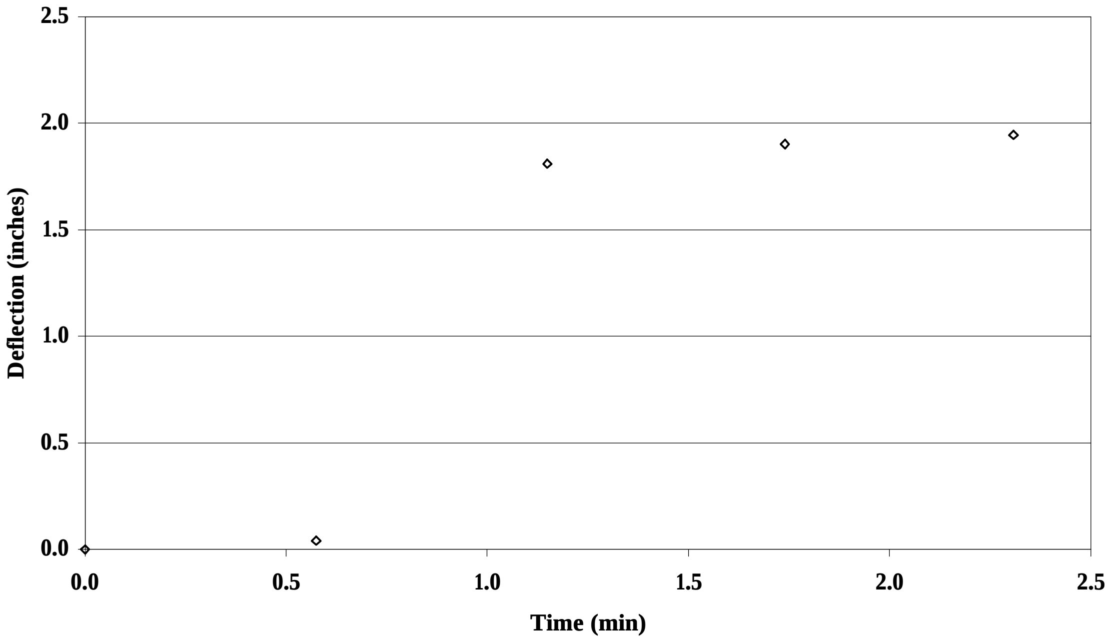
APPENDIX B

DISPLACEMENT VS. TIME PLOTS

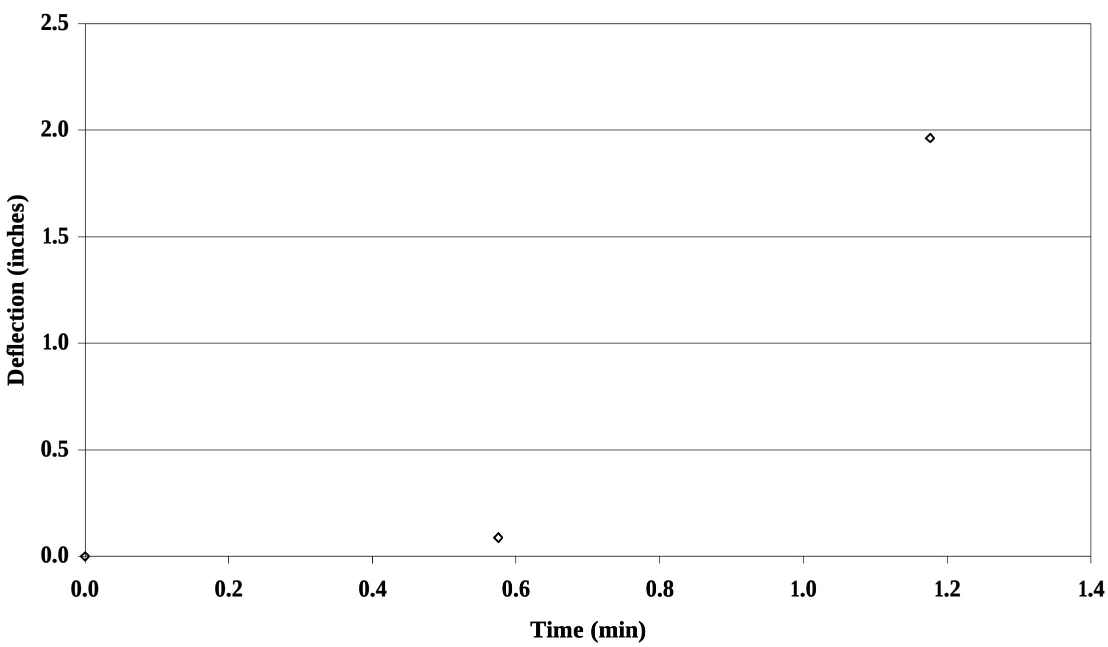
INTRODUCTION

Displacement versus time plots were created for each specimen tested as part of the load-duration investigation. These plots can be found on the following pages and are arranged by formulation in the following order: PVC, HDPE 8, HDPE 67.5, and HDPE 67.5 w/ MAPE. Within each formulation the plots are in descending order of applied stress level. Some plots were not included, typically at the highest stress level, because the member failed during upload. Other plots contain discontinuities that may be attributed to partial failures, as is observed in load-duration testing of wood products, or to mechanical problems with the testing apparatus. In the cases where it appeared that a mechanical problem was the cause of the discontinuity, the test was repeated using a specimen taken from the same extrusion run. If additional members were not available, consideration was given, in analysis of the data, to the fact that a mechanical difficulty may have caused the anomaly.

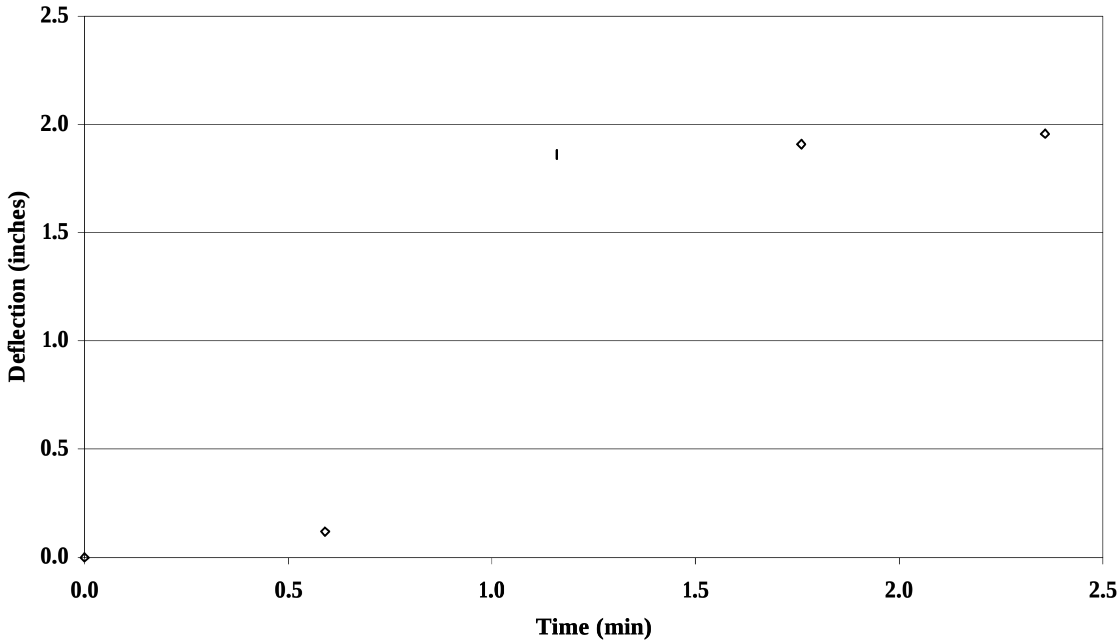
Deflection vs. Time at 81.3% of Ultimate
PVC 50/50 Specimen # 80



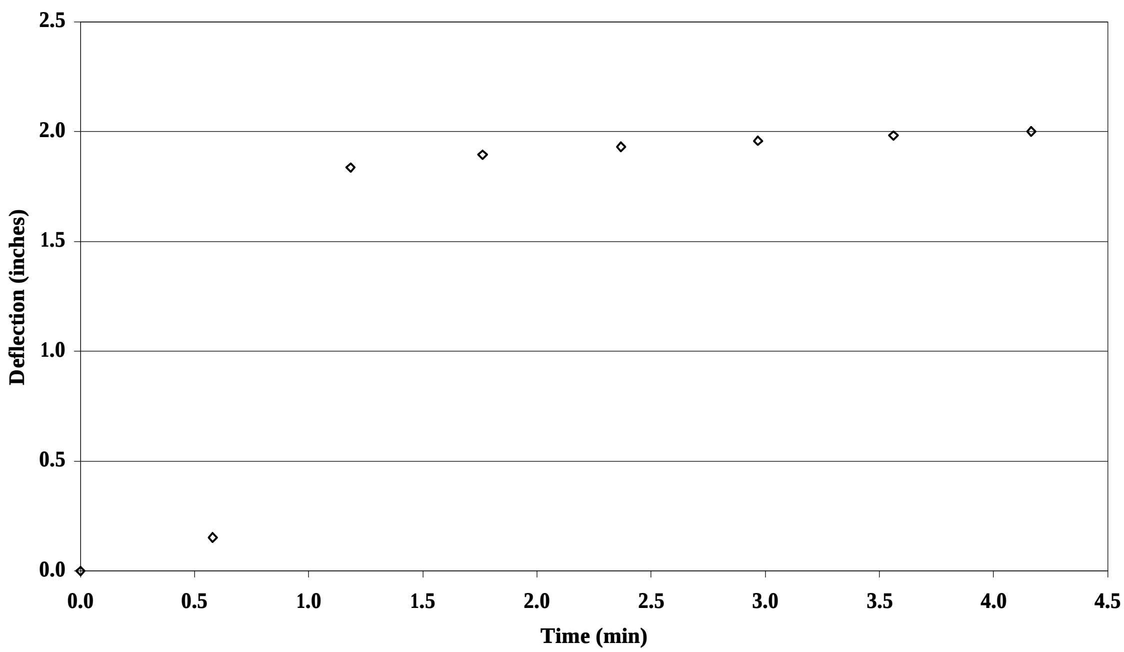
Deflection vs. Time at 81.3% of Ultimate
PVC 50/50 Specimen # 85

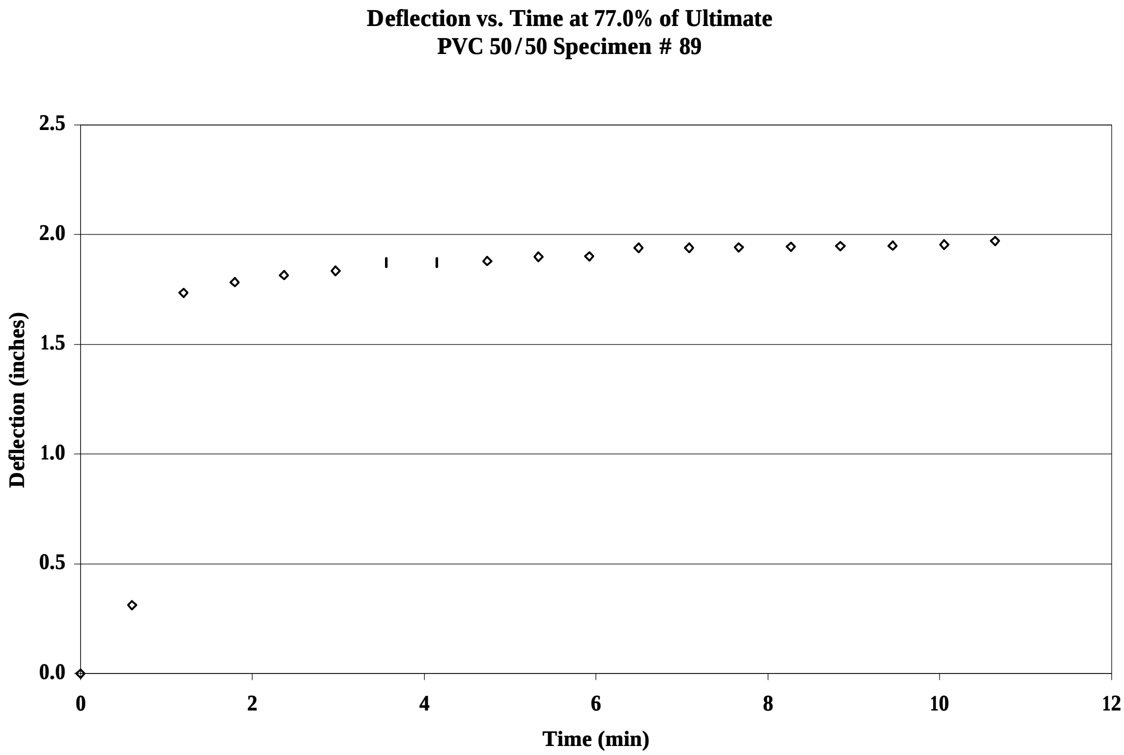


Deflection vs. Time at 81.3% of Ultimate
PVC 50/50 Specimen # 95

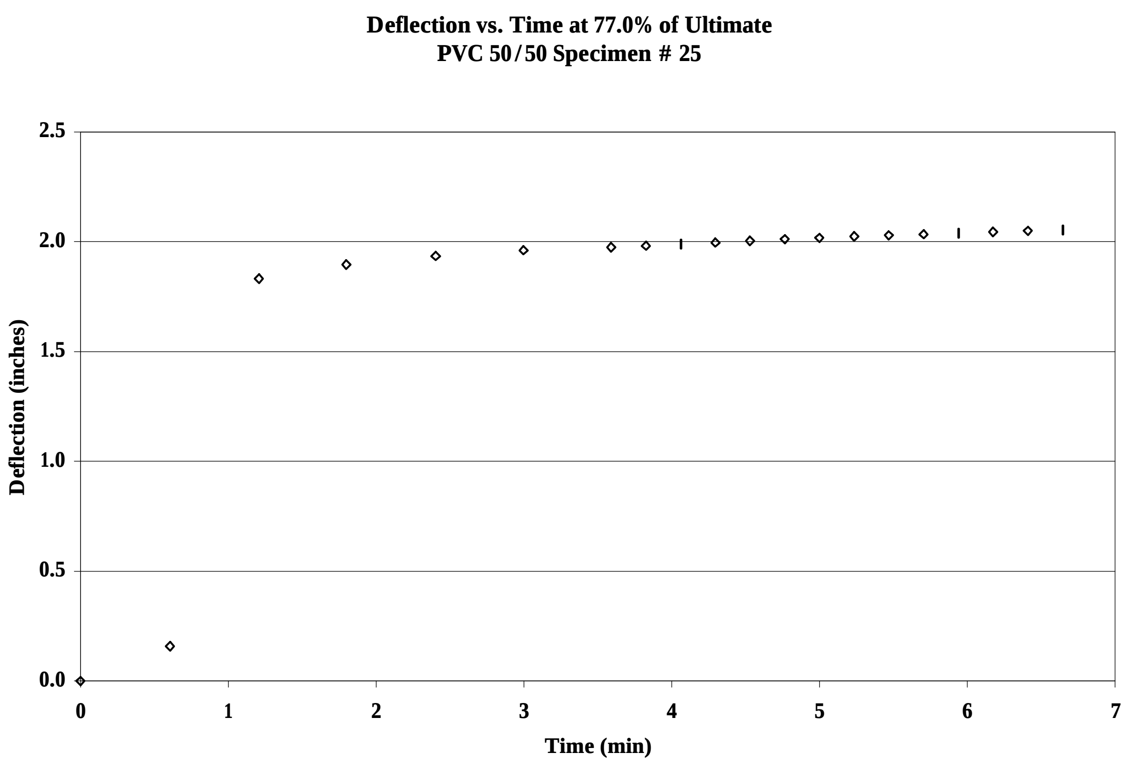


Deflection vs. Time at 77.0% of Ultimate
PVC 50/50 Specimen # 76



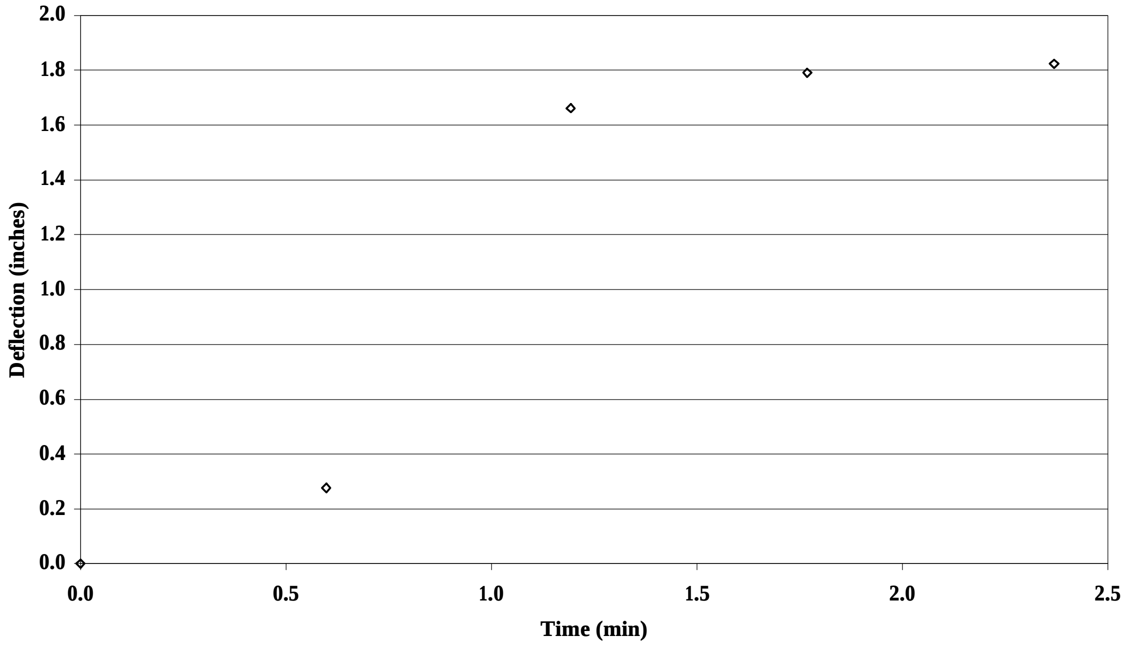


Deflection vs. Time at 77.0% of Ultimate
PVC 50/50 Specimen # 89
2.5
2.0
1.5
1.0
0.5
0.0
Deflection (inches)
0
2
4
6
8
10
12
Time (min)

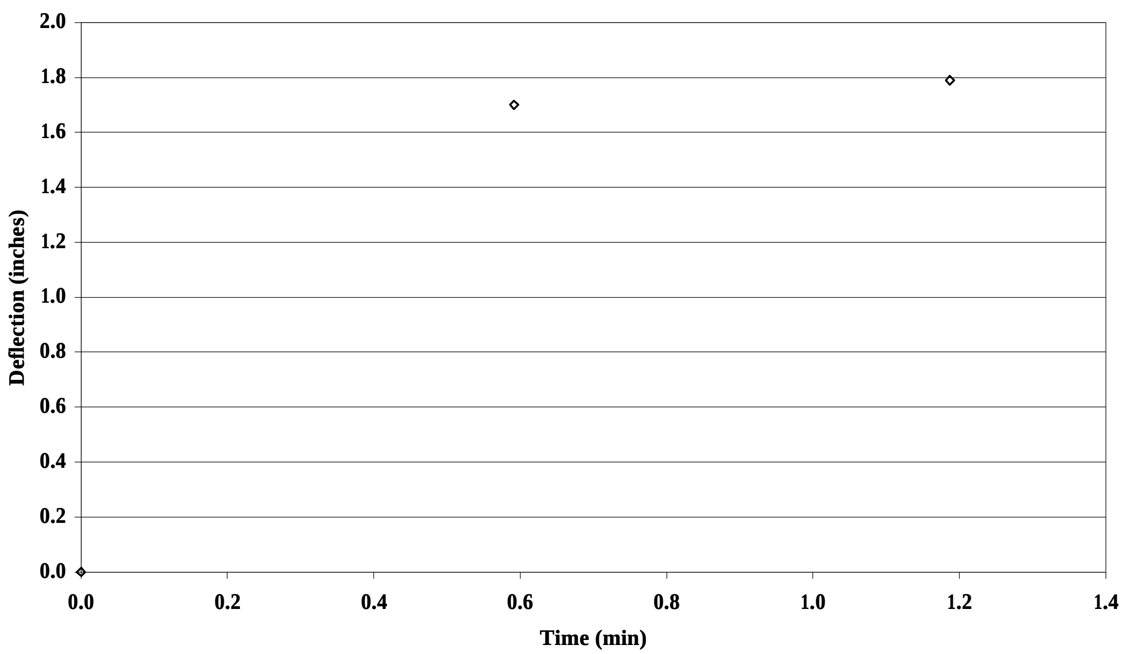


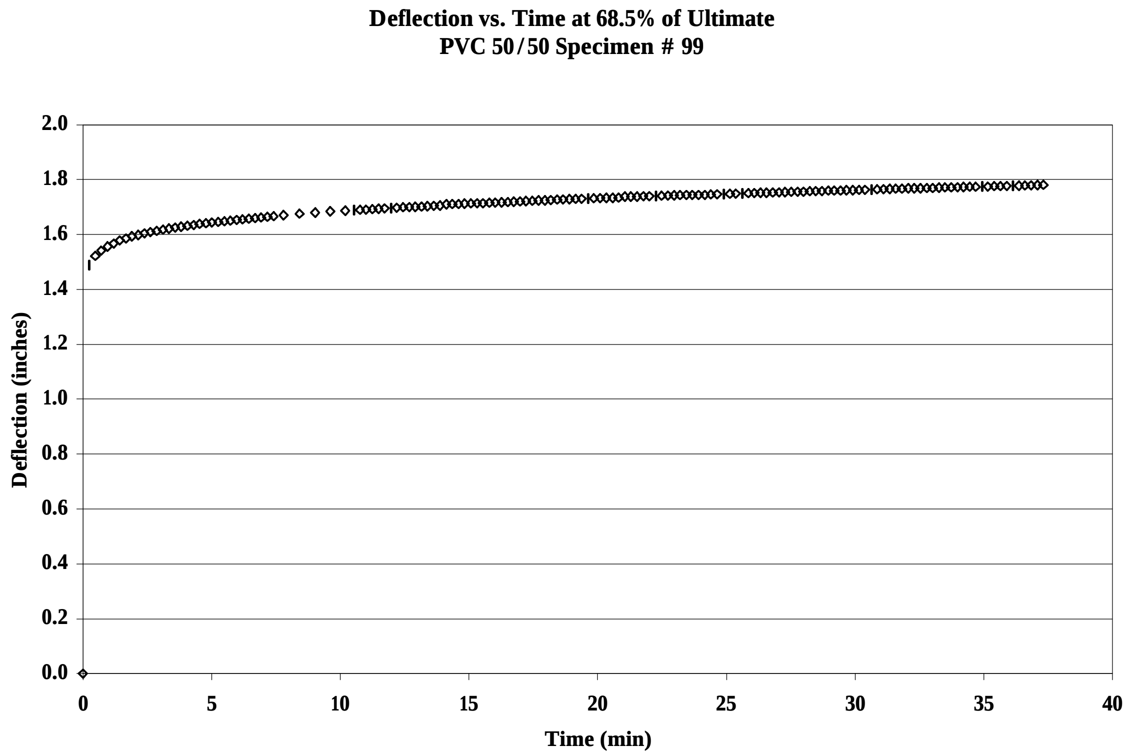
Deflection vs. Time at 77.0% of Ultimate
PVC 50/50 Specimen # 25
2.5
2.0
1.5
1.0
0.5
0.0
Deflection (inches)
0
1
2
3
4
5
6
7
Time (min)

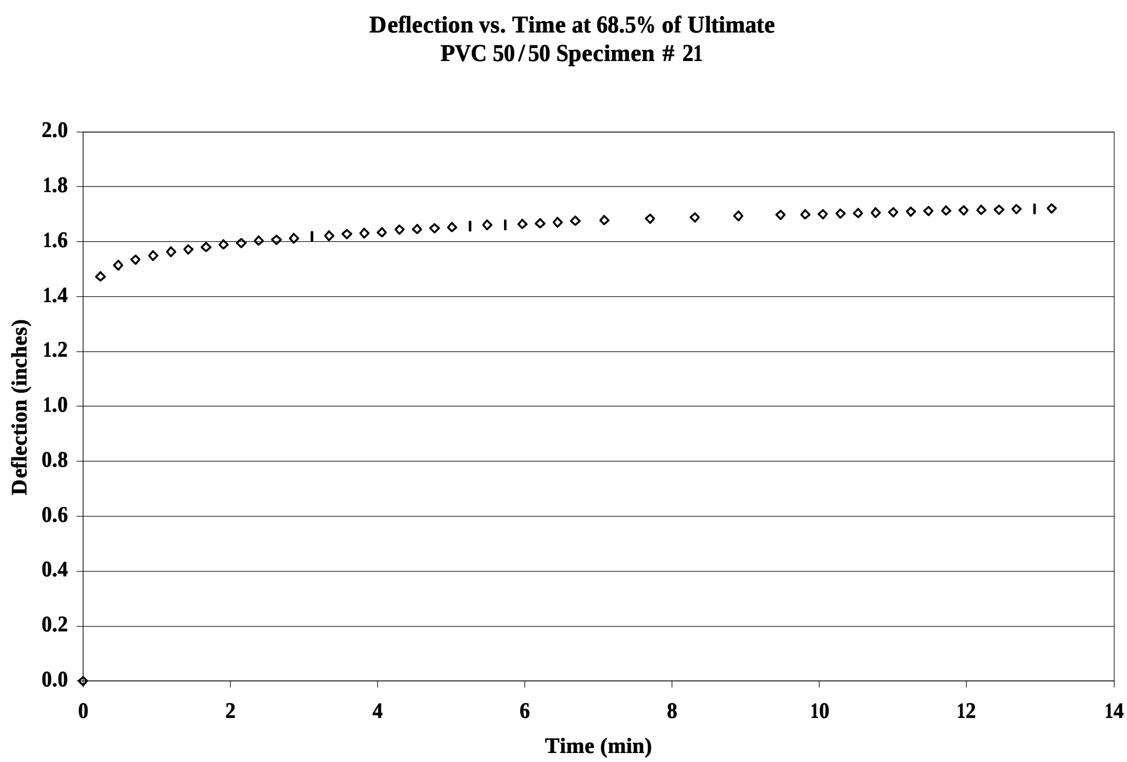
Deflection vs. Time at 77.0% of Ultimate
PVC 50/50 Specimen # 28

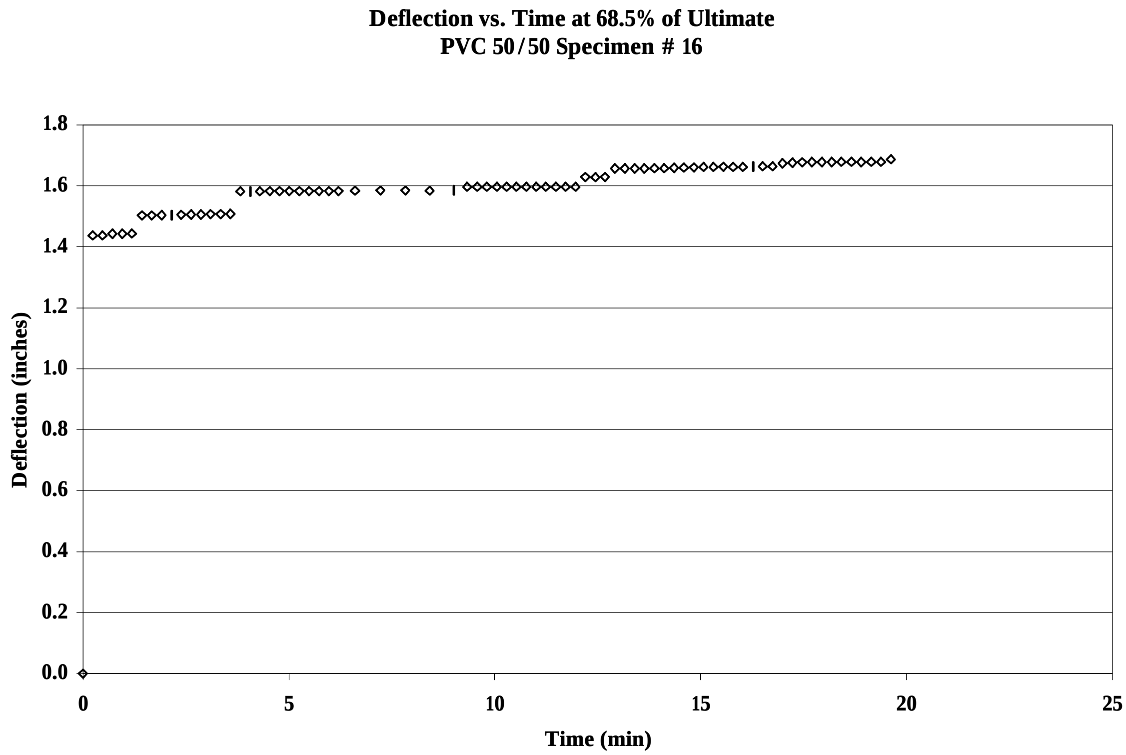


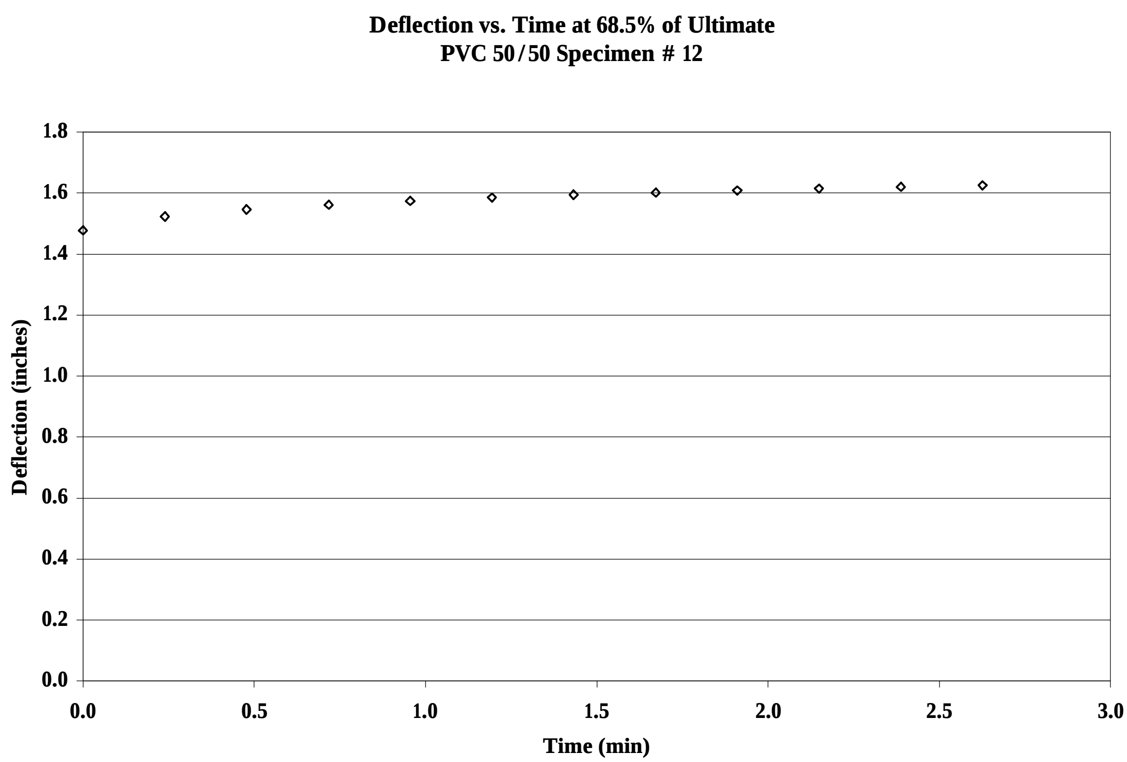
Deflection vs. Time at 77.0% of Ultimate
PVC 50/50 Specimen # 10



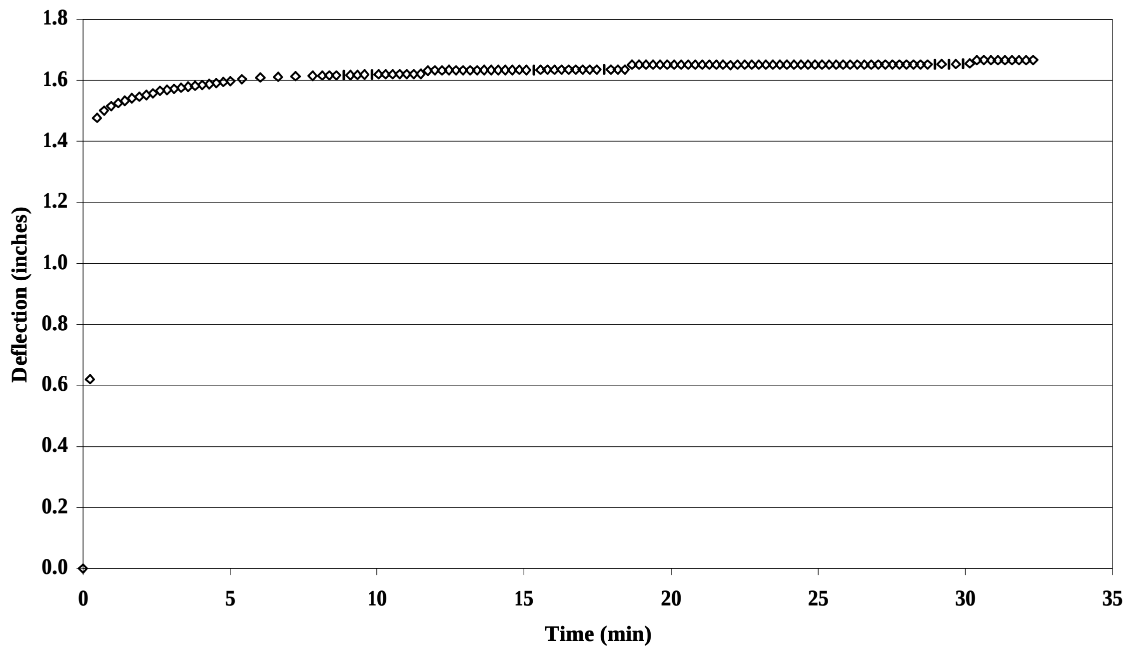

Deflection vs. Time at 68.5% of Ultimate
PVC 50/50 Specimen # 99
Deflection (inches)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
40
Time (min)


Deflection vs. Time at 68.5% of Ultimate
PVC 50/50 Specimen # 21
Deflection (inches)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
12
14
Time (min)

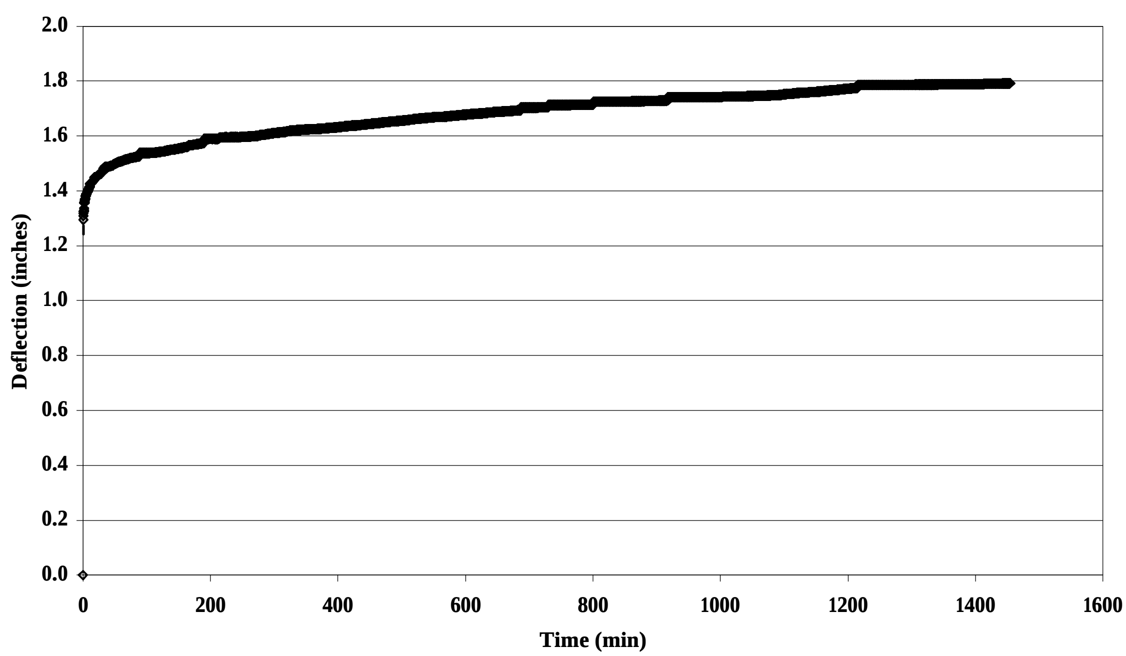

Deflection vs. Time at 68.5% of Ultimate
PVC 50/50 Specimen # 16
Deflection (inches)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
Time (min)


Deflection vs. Time at 68.5% of Ultimate
PVC 50/50 Specimen # 12
Deflection (inches)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (min)

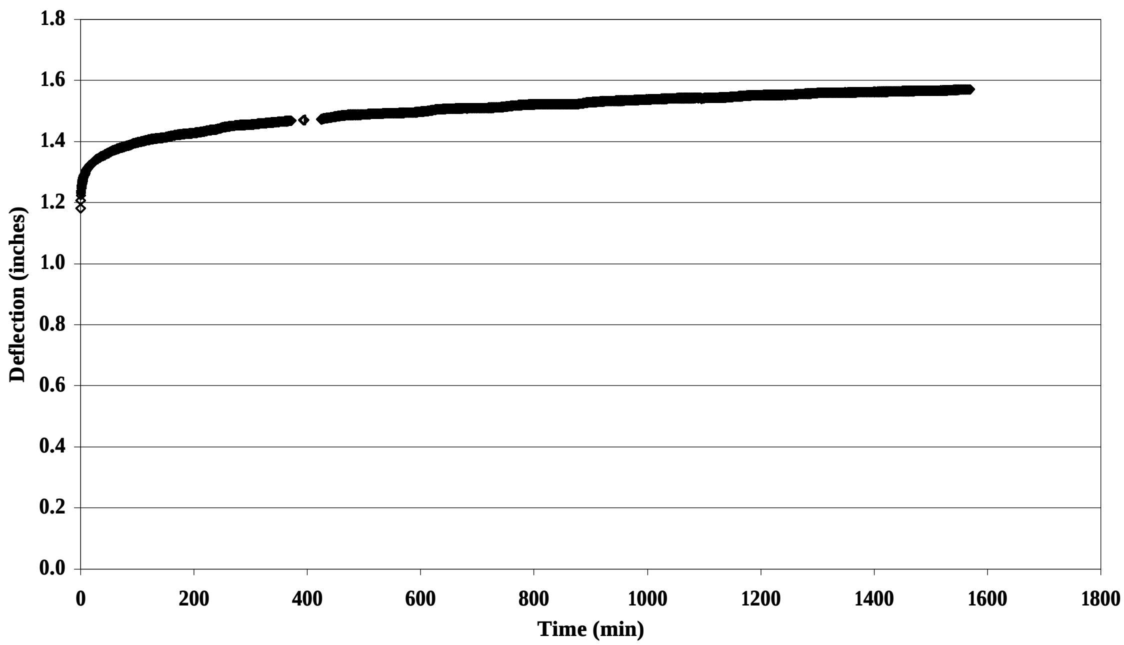
Deflection vs. Time at 68.5% of Ultimate
PVC 50/50 Specimen # 11



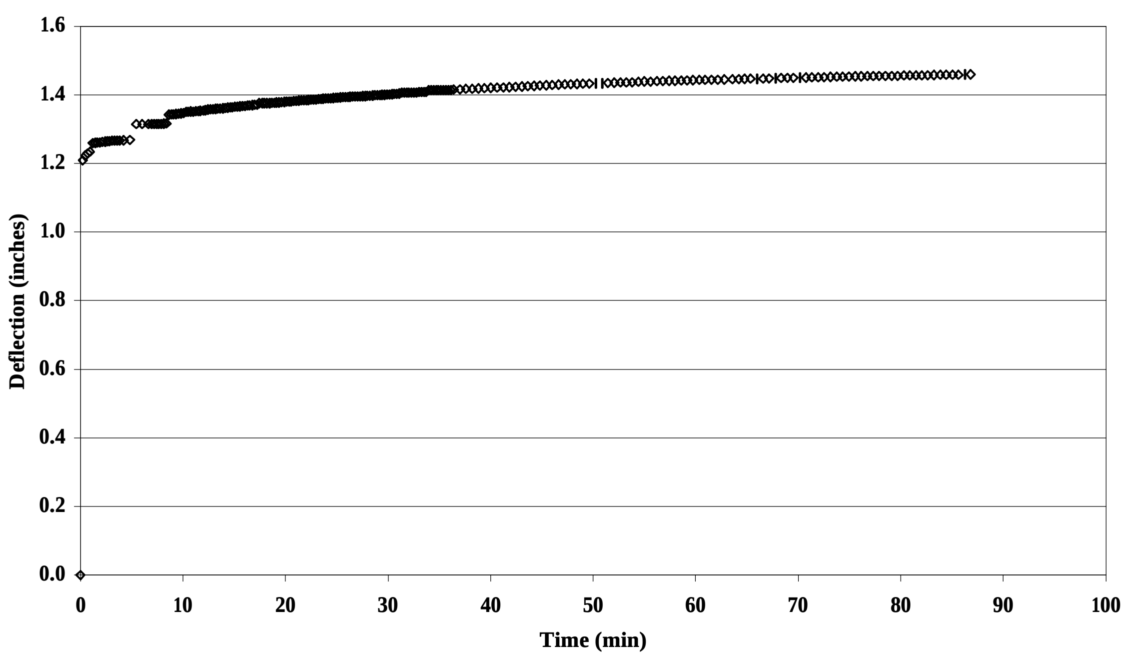
Deflection vs. Time at 59.9% of Ultimate
PVC 50/50 Specimen # 90



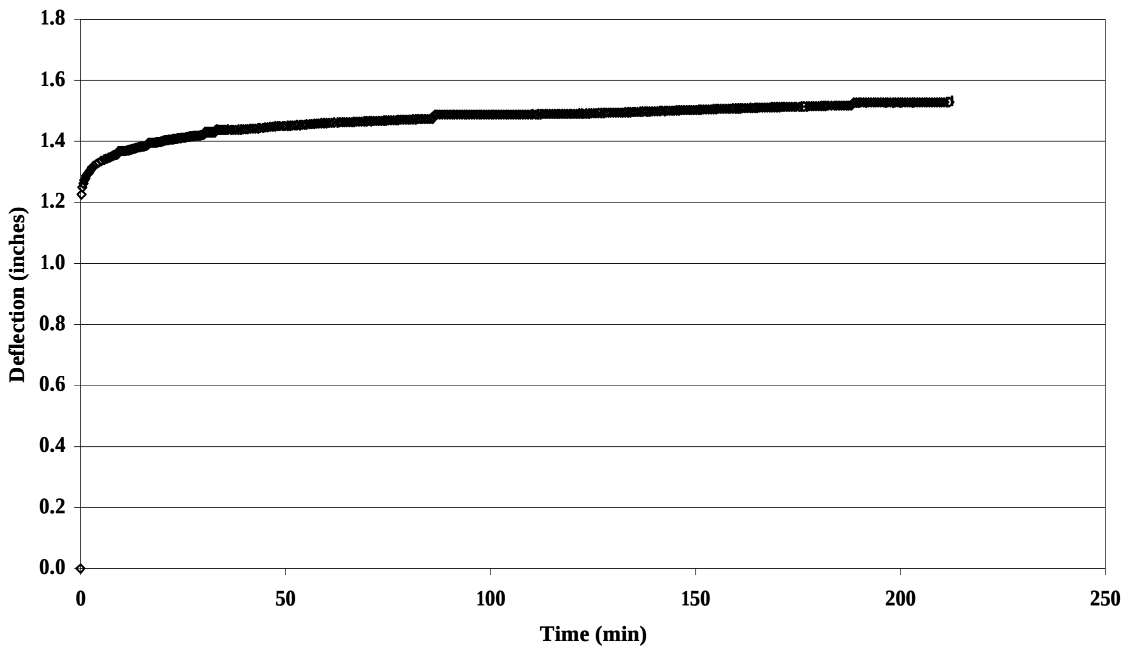
Deflection vs. Time at 59.9% of Ultimate
PVC 50/50 Specimen # 91



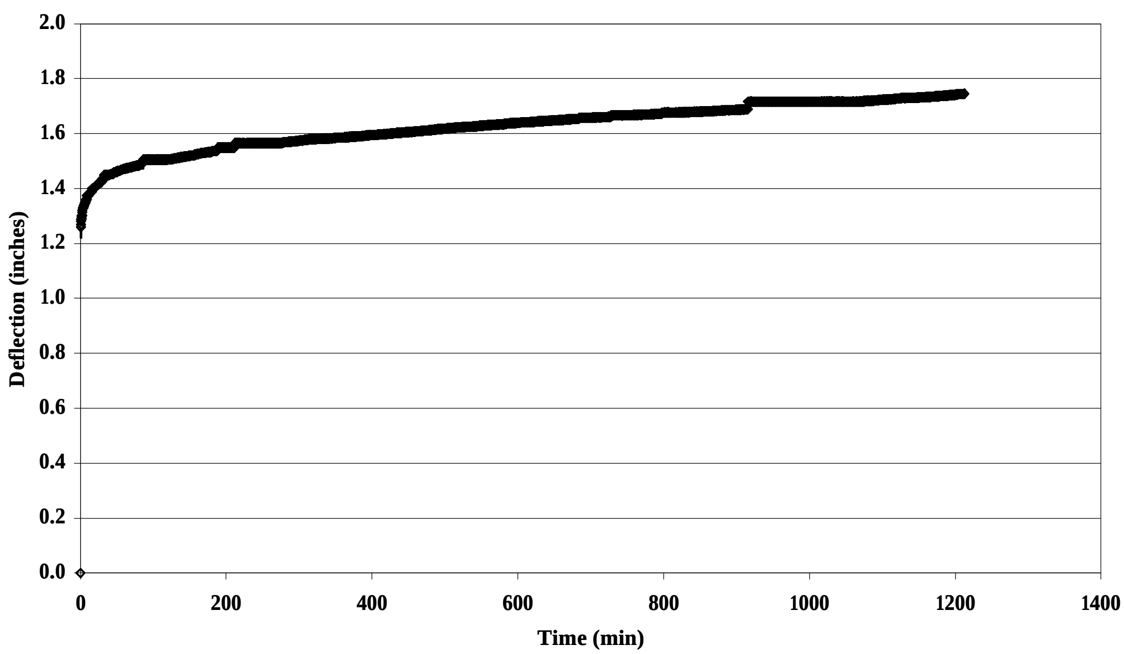
Deflection vs. Time at 59.9% of Ultimate
PVC 50/50 Specimen # 15



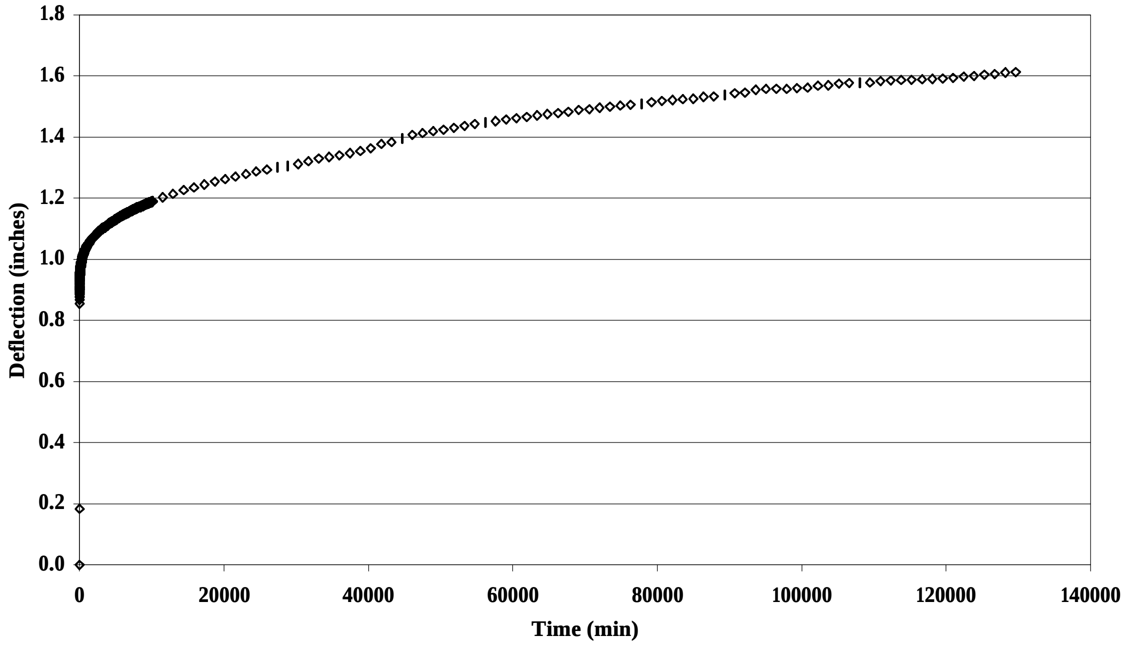
Deflection vs. Time at 59.9% of Ultimate
PVC 50/50 Specimen # 84



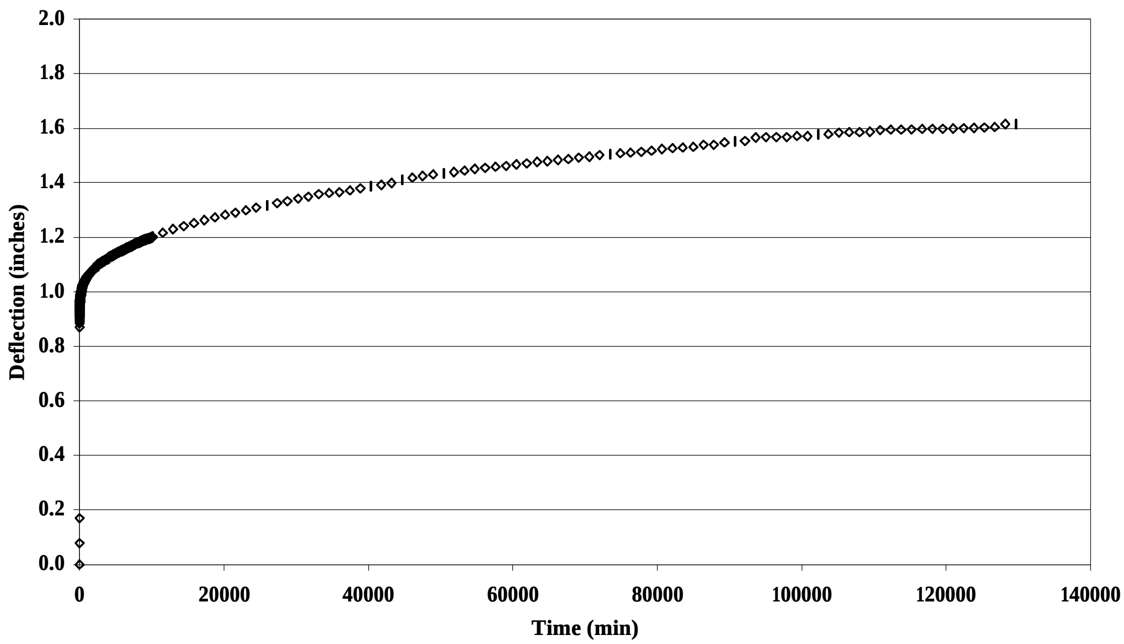
Deflection vs. Time at 59.9% of Ultimate
PVC 50/50 Specimen # 17



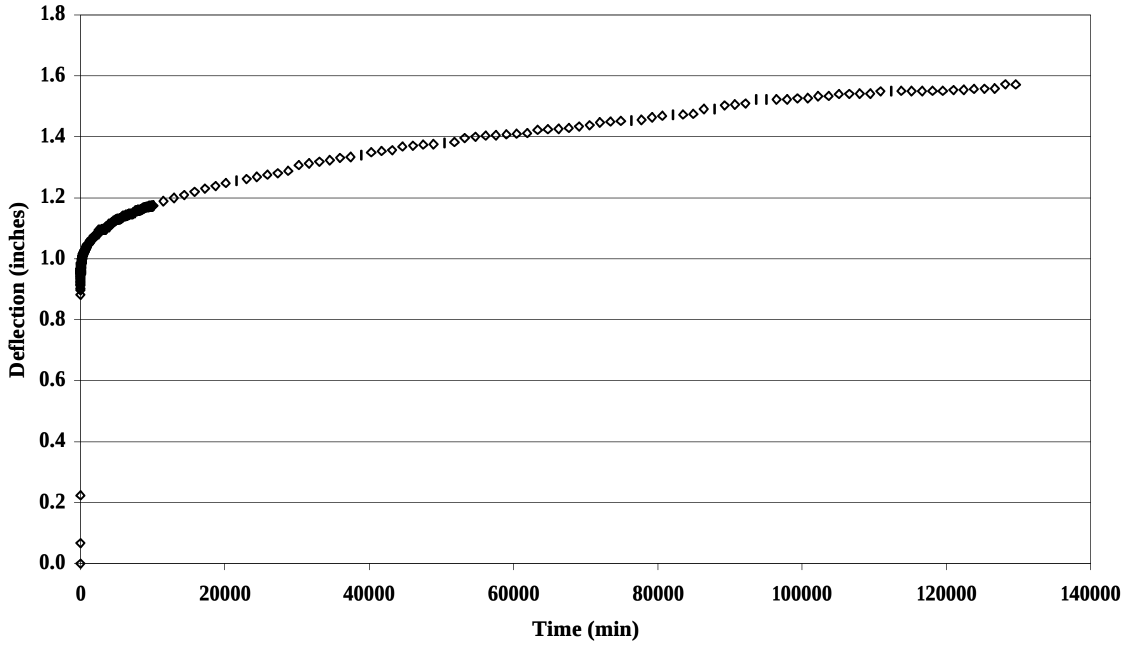
Deflection vs. Time at 42.8% of Ultimate
PVC 50/50 Specimen # 92



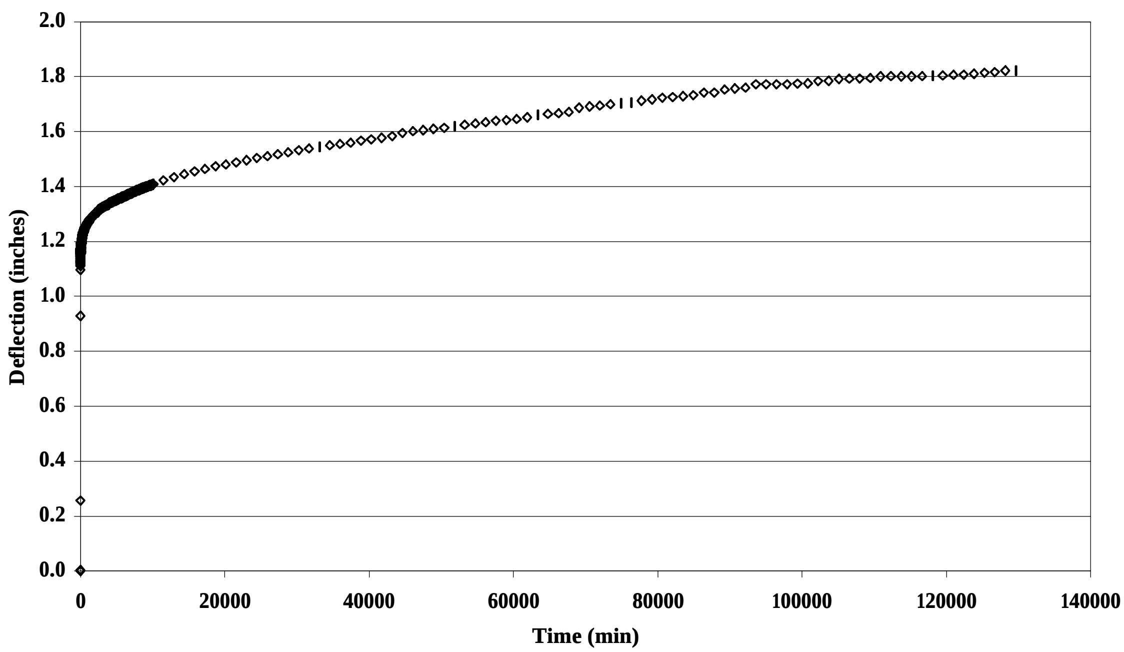
Deflection vs. Time at 42.8% of Ultimate
PVC 50/50 Specimen # 93



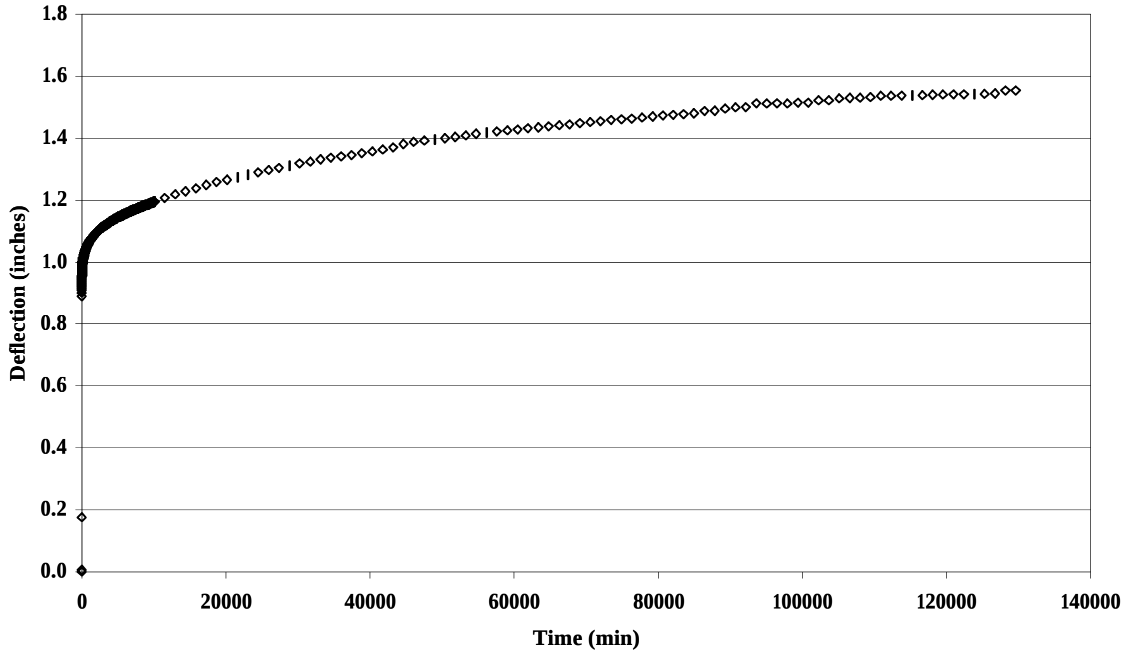
Deflection vs. Time at 42.8% of Ultimate
PVC 50/50 Specimen # 83



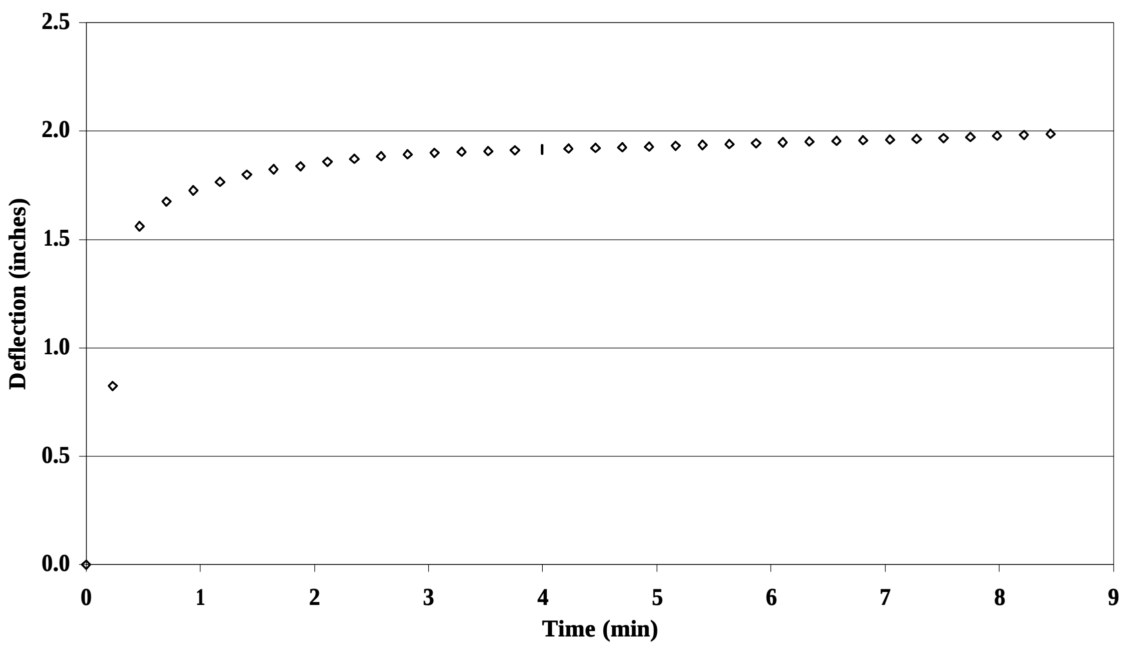
Deflection vs. Time at 42.8% of Ultimate
PVC 50/50 Specimen # 26

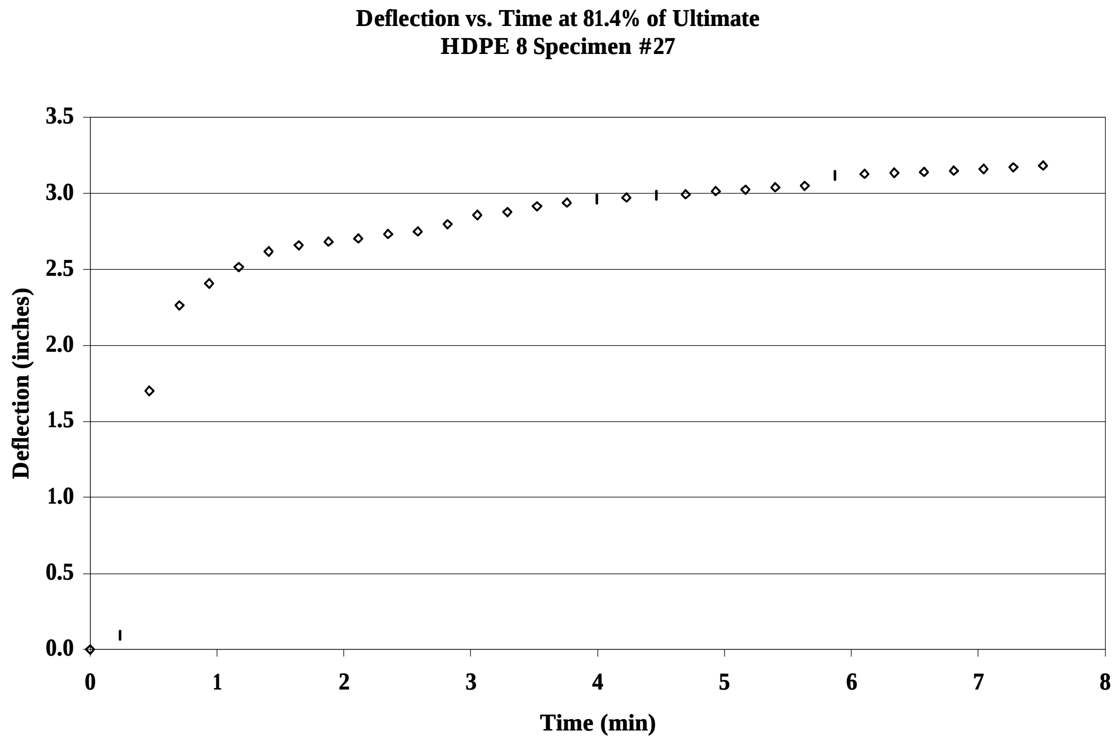


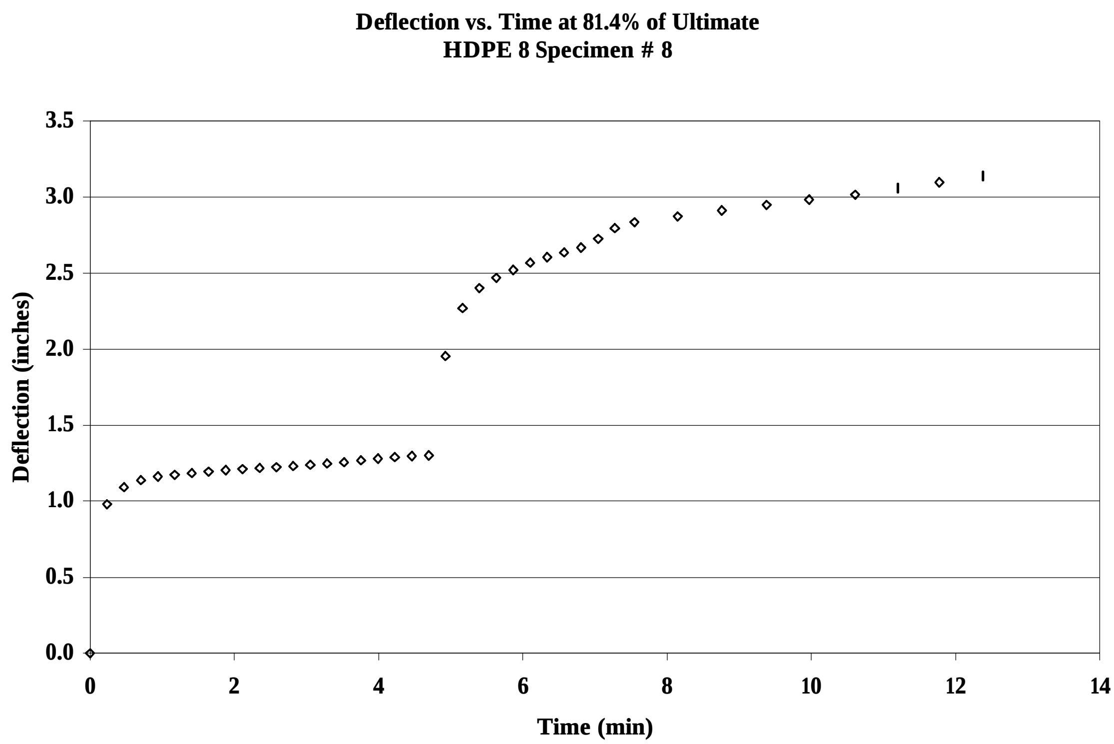
Deflection vs. Time at 42.8% of Ultimate
PVC 50/50 Specimen # 22



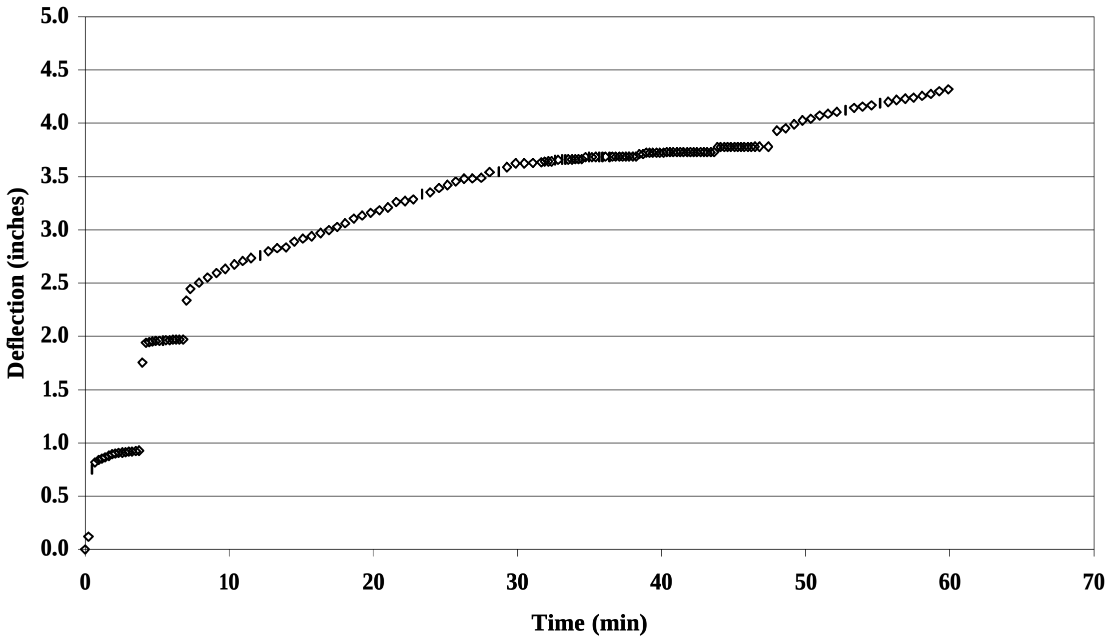
Deflection vs. Time at 81.4% of Ultimate
HDPE 8 Specimen # 9



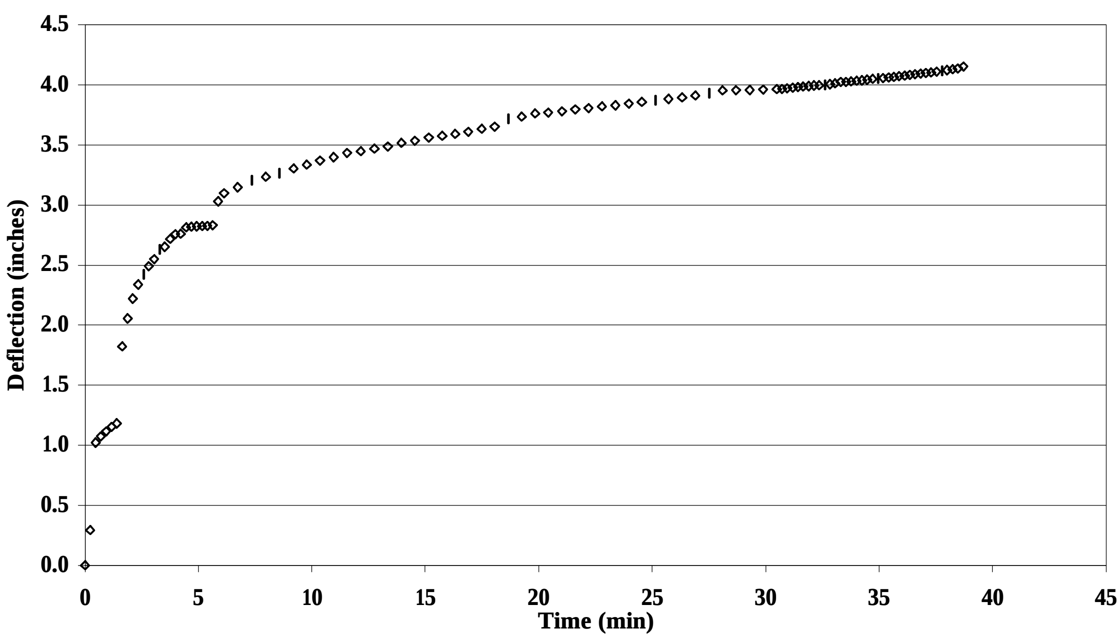

Deflection vs. Time at 81.4% of Ultimate
HDPE 8 Specimen #27
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Deflection (inches)
0
1
2
3
4
5
6
7
8
Time (min)

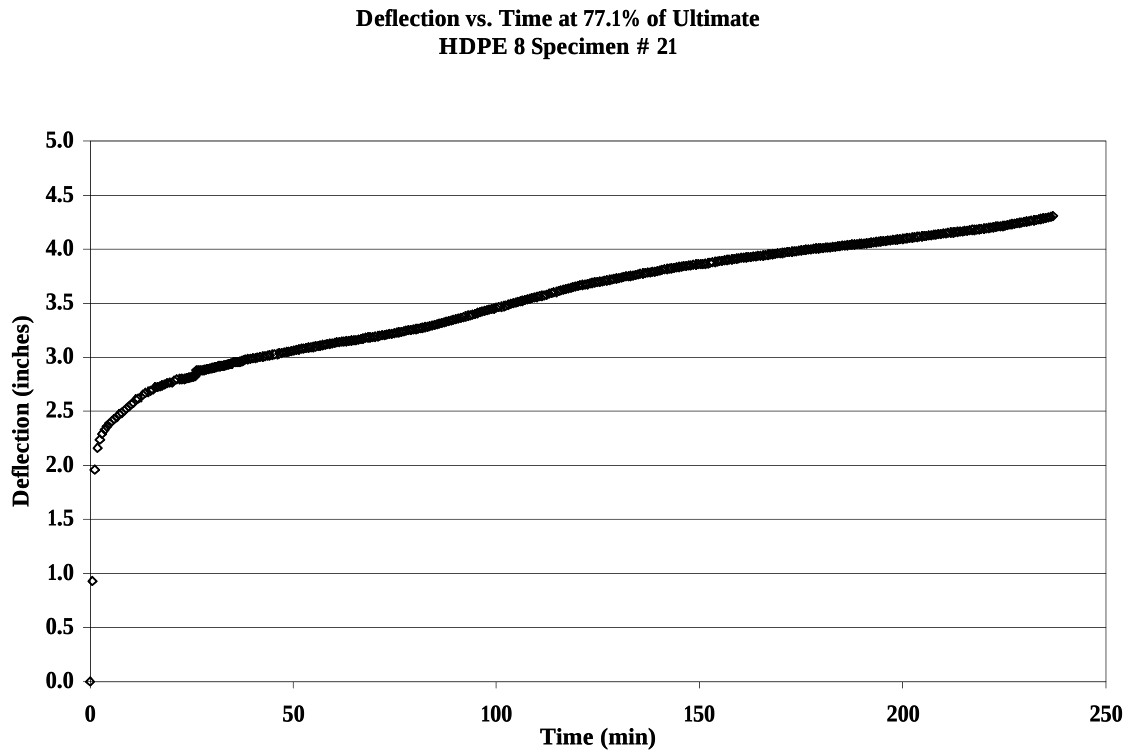

Deflection vs. Time at 81.4% of Ultimate
HDPE 8 Specimen # 8
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Deflection (inches)
0
2
4
6
8
10
12
14
Time (min)

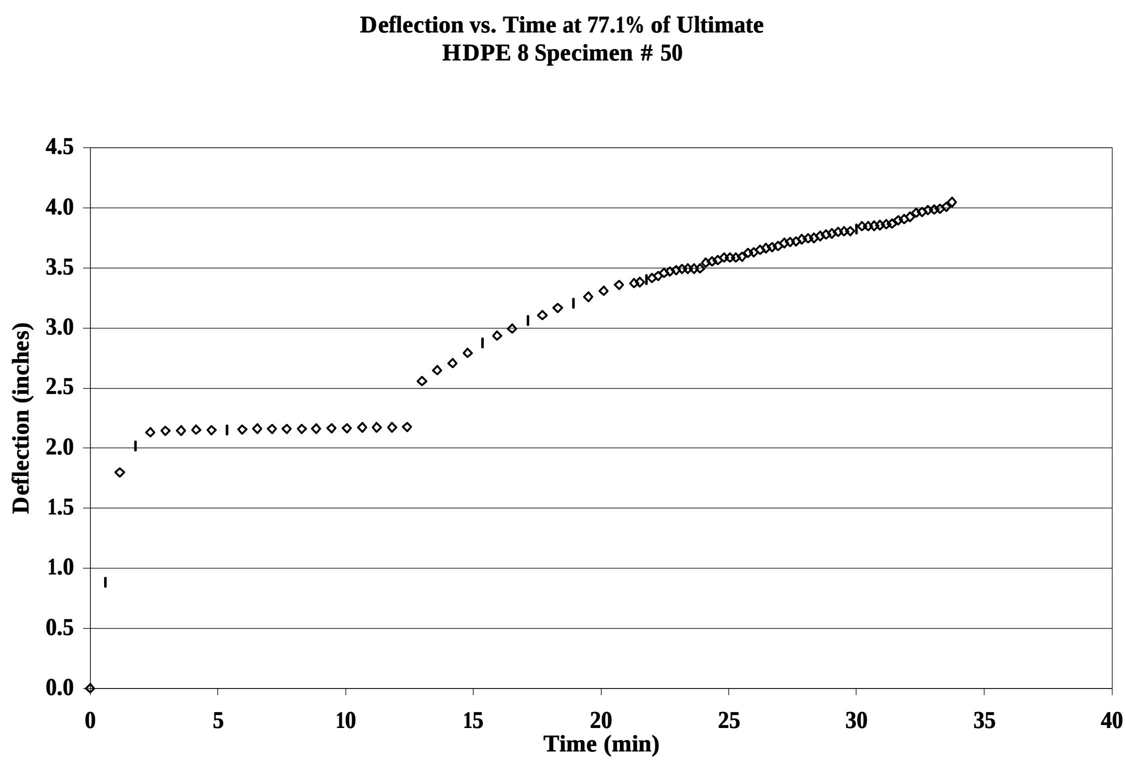
Deflection vs. Time at 81.4% of Ultimate
HDPE 8 Specimen # 52



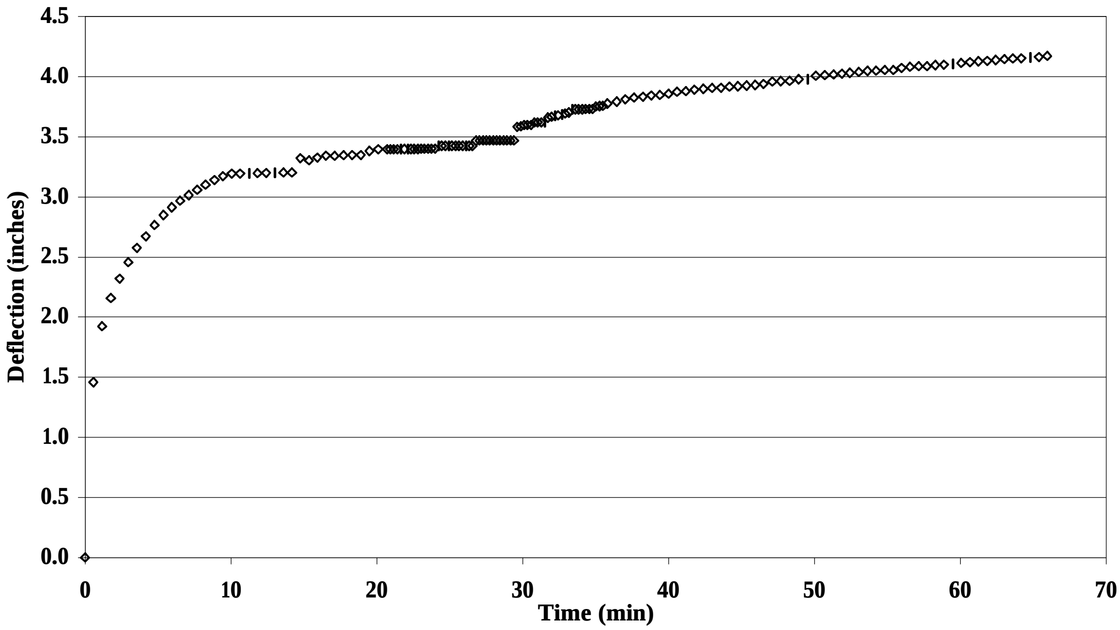
Deflection vs. Time at 81.4% of Ultimate
HDPE 8 Specimen # 24



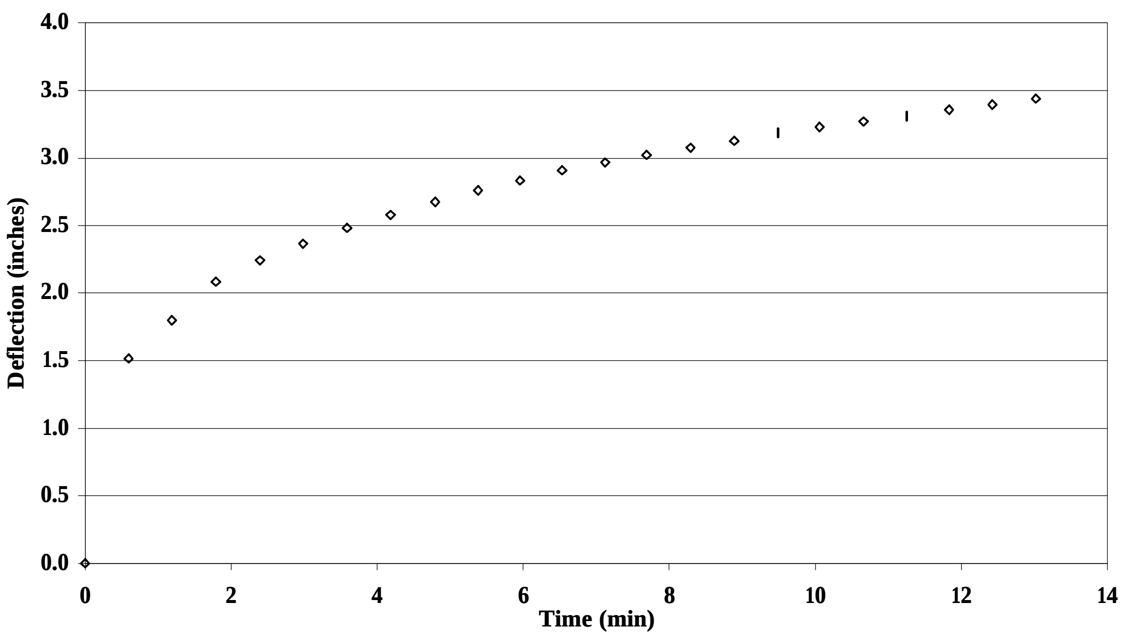

Deflection vs. Time at 77.1% of Ultimate
HDPE 8 Specimen # 21
Deflection (inches)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
0
50
100
150
200
250
Time (min)


Deflection vs. Time at 77.1% of Ultimate
HDPE 8 Specimen # 50
Deflection (inches)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
0
5
10
15
20
25
30
35
40
Time (min)

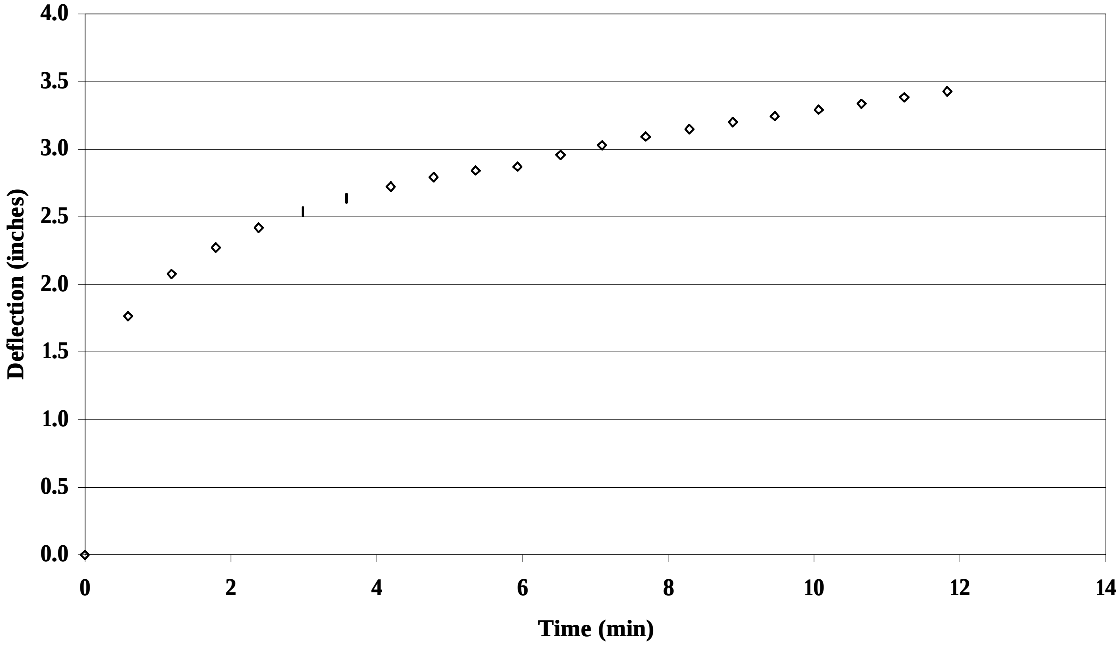
Deflection vs. Time at 77.1% of Ultimate
HDPE 8 Specimen # 31



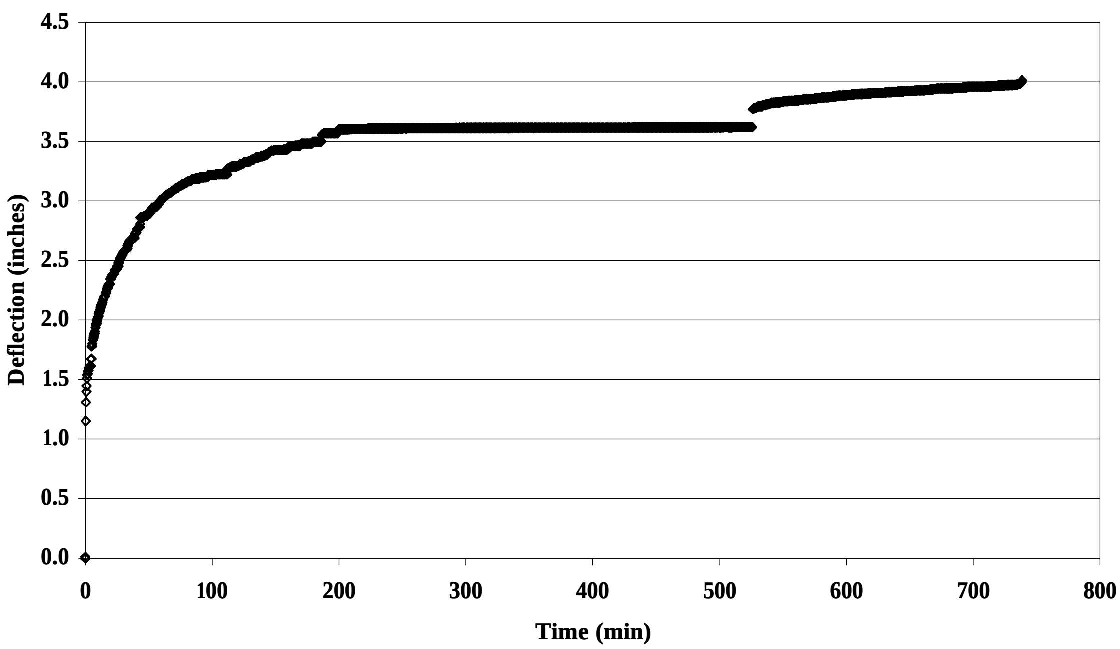
Deflection vs. Time at 77.1% of Ultimate
HDPE 8 Specimen # 55



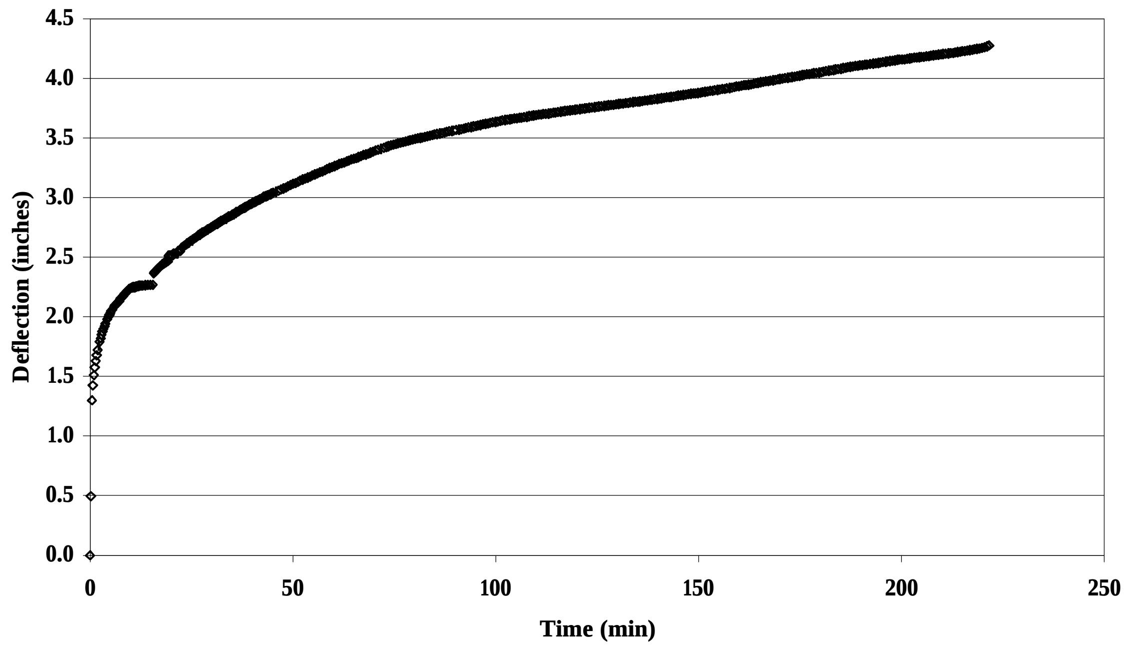
Deflection vs. Time at 77.1% of Ultimate
HDPE 8 Specimen # 42



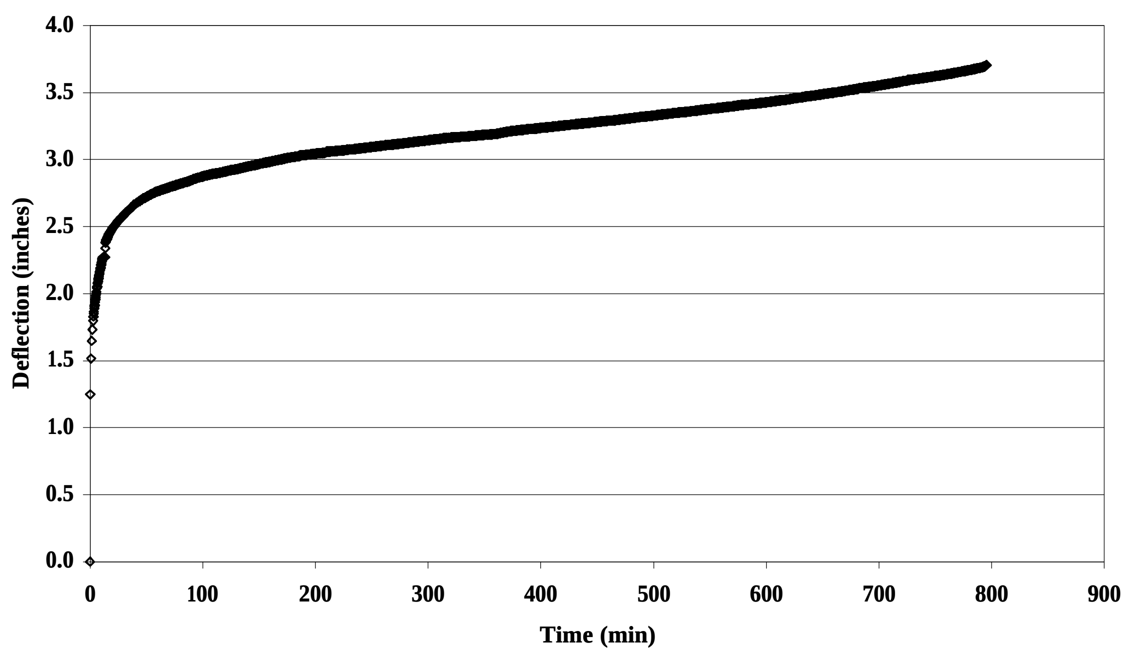
Deflection vs. Time at 68.6% of Ultimate
HDPE 8 Specimen # 19



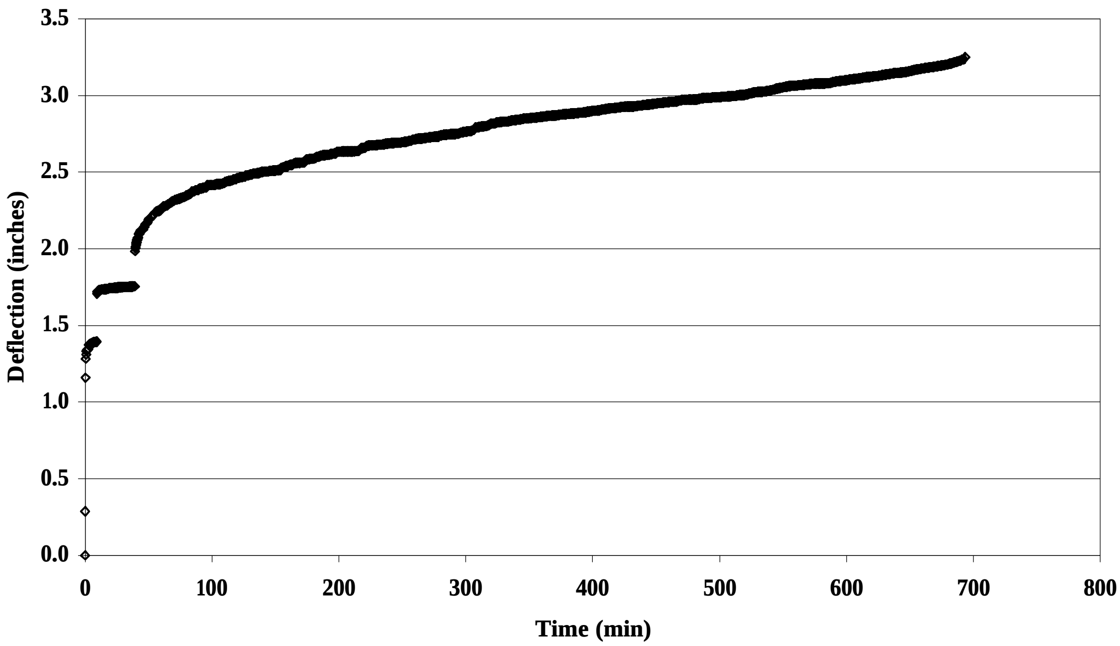
Deflection vs. Time at 68.6% of Ultimate
HDPE 8 Specimen # 33



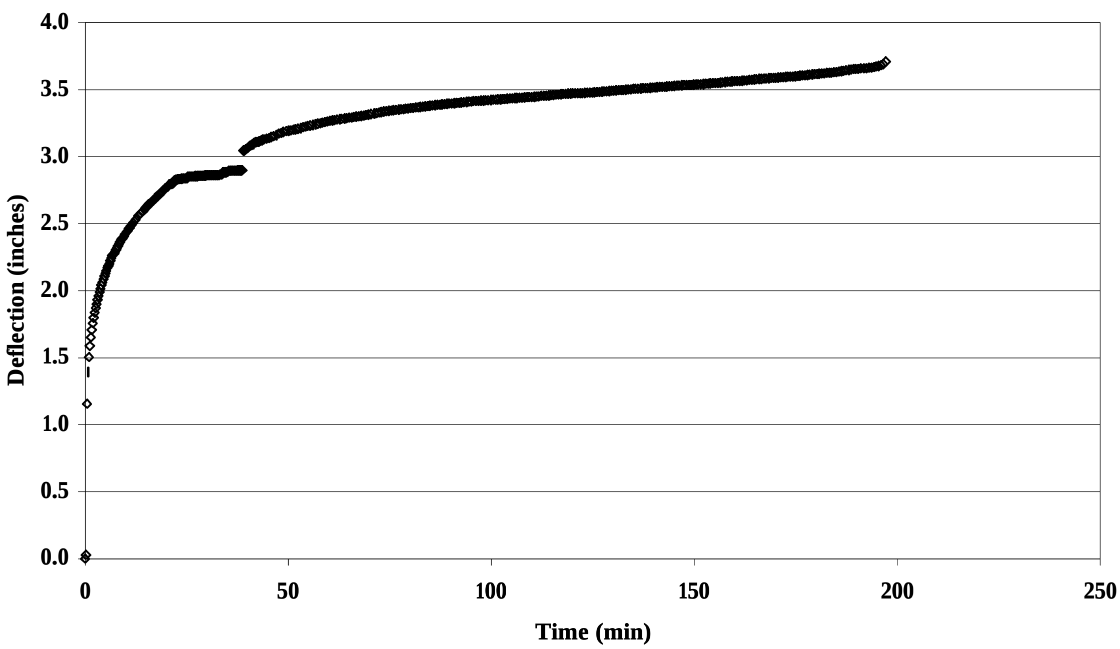
Deflection vs. Time at 68.6% of Ultimate
HDPE 8 Specimen # 25



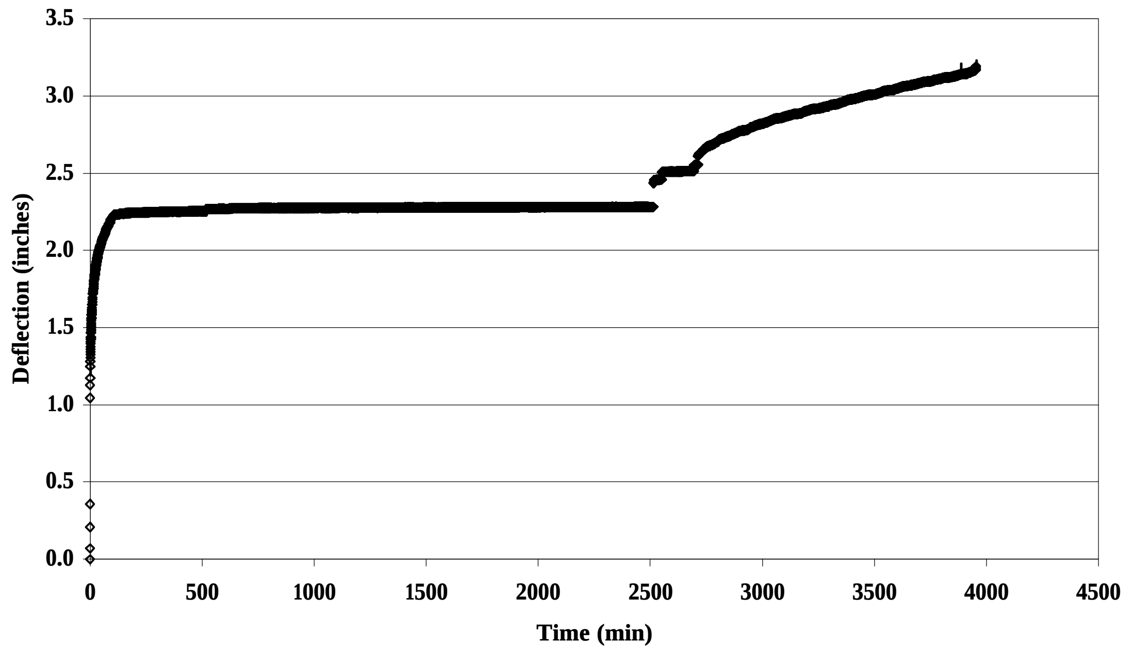
Deflection vs. Time at 68.6% of Ultimate
HDPE 8 Specimen # 36



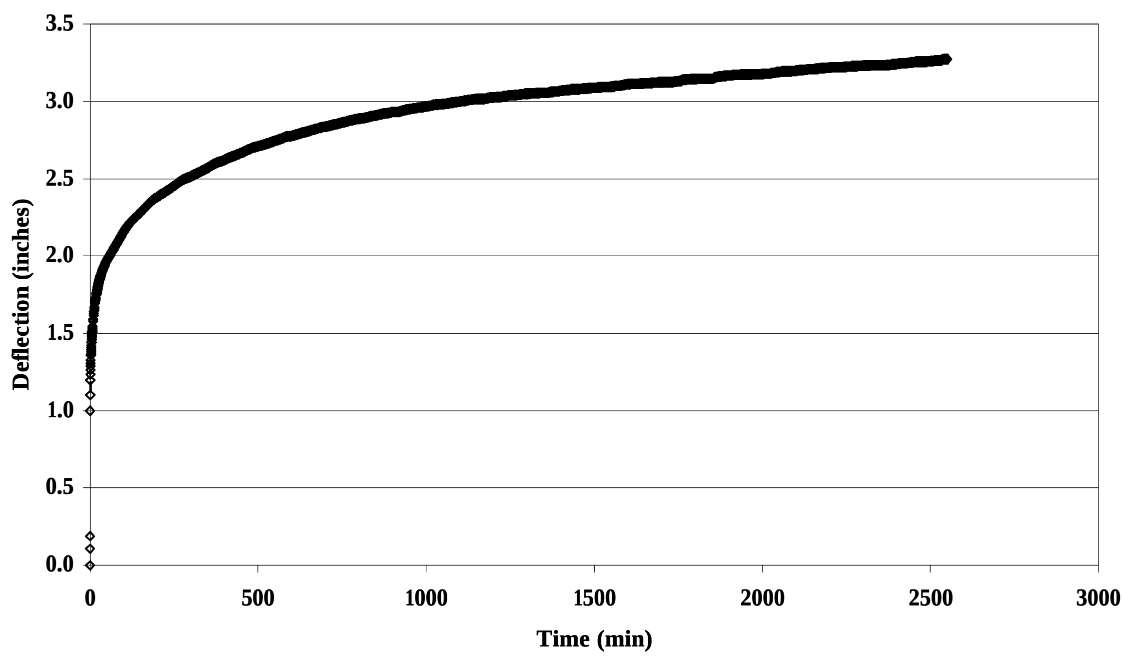
Deflection vs. Time at 68.6% of Ultimate
HDPE 8 Specimen # 16



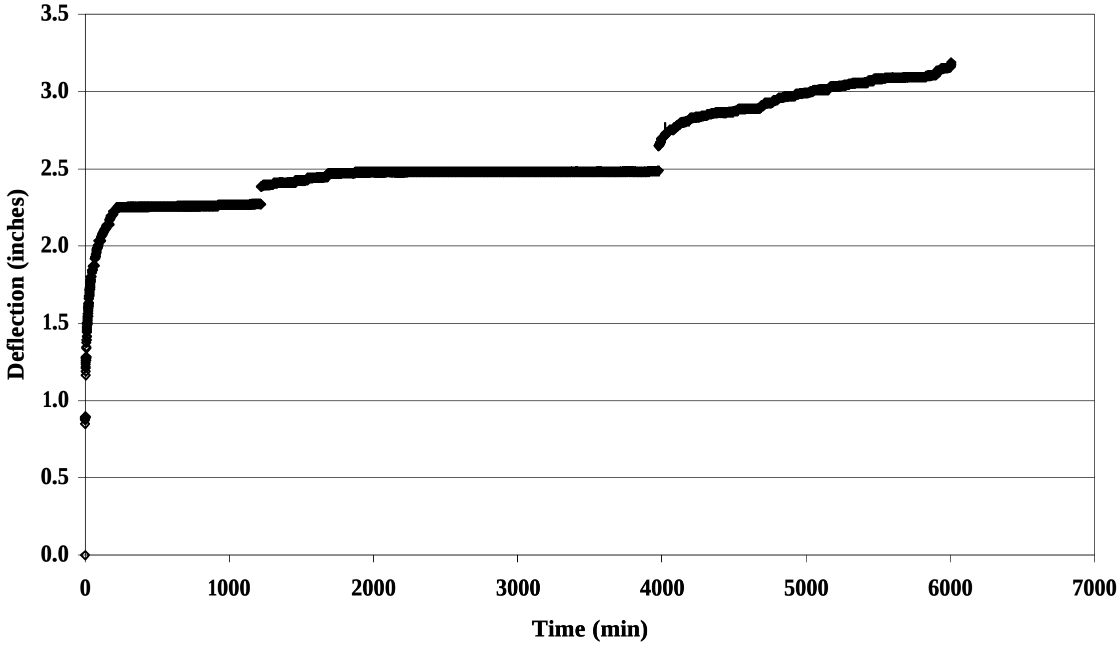
Deflection vs. Time at 60.0% of Ultimate
HDPE 8 Specimen # 35



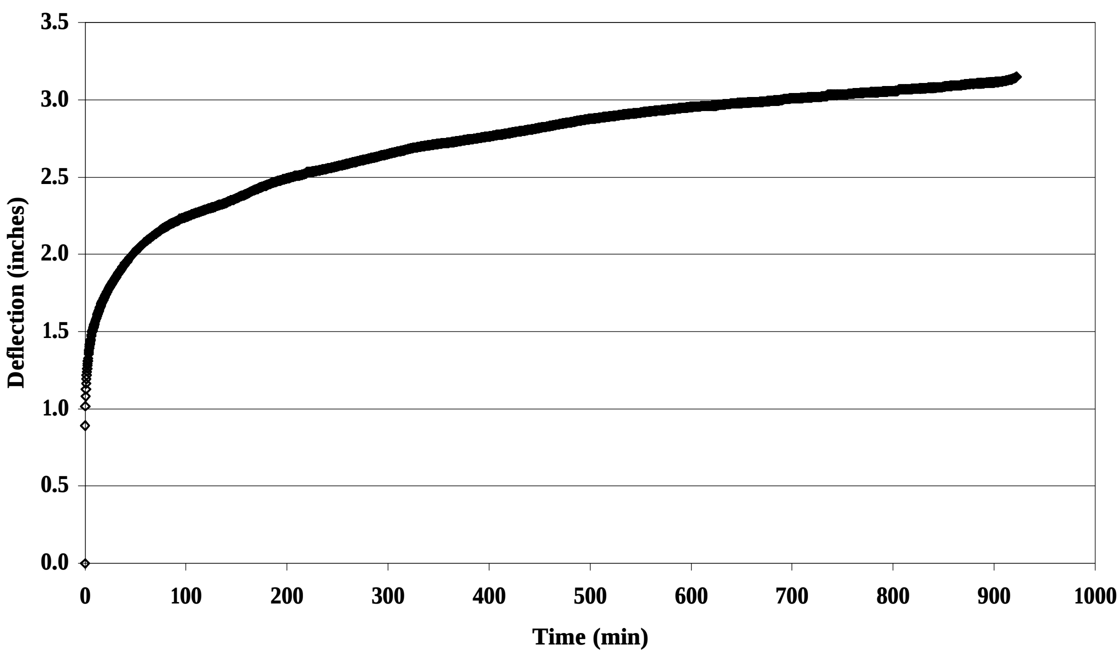
Deflection vs. Time at 60.0% of Ultimate
HDPE 8 Specimen # 6



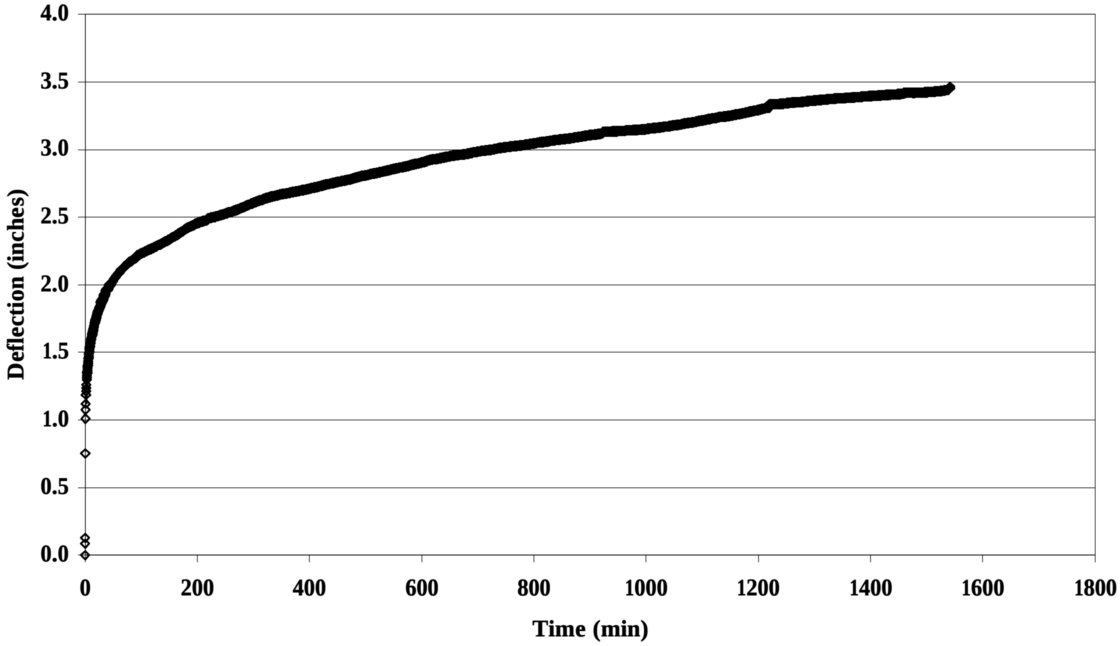
Deflection vs. Time at 60.0% of Ultimate
HDPE 8 Specimen # 1



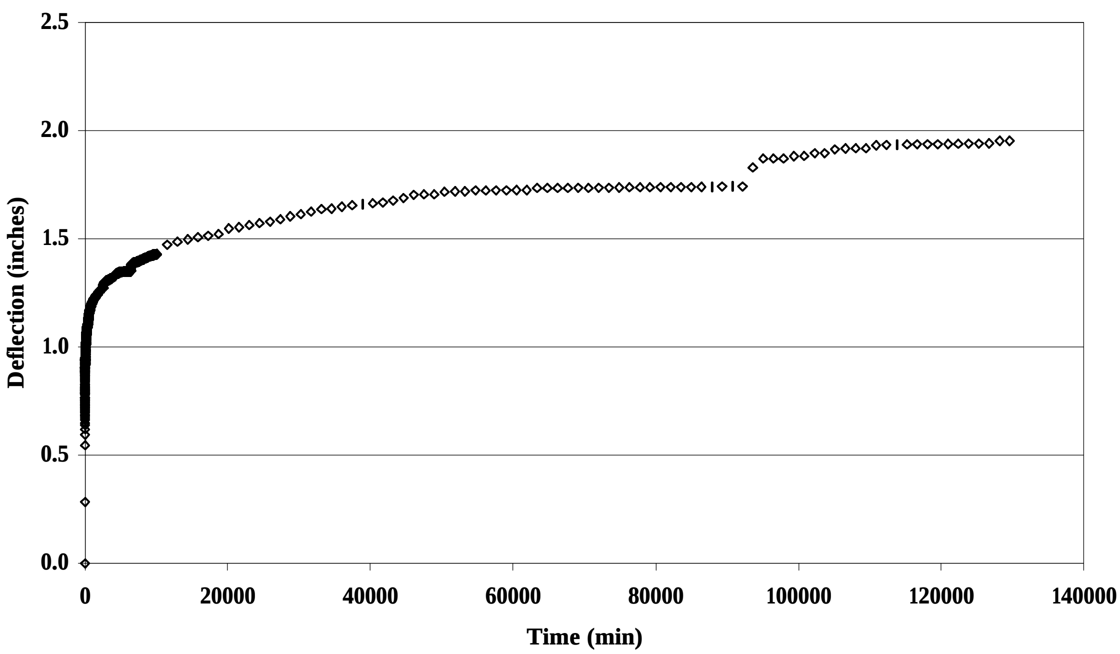
Deflection vs. Time at 60.0% of Ultimate
HDPE 8 Specimen # 28



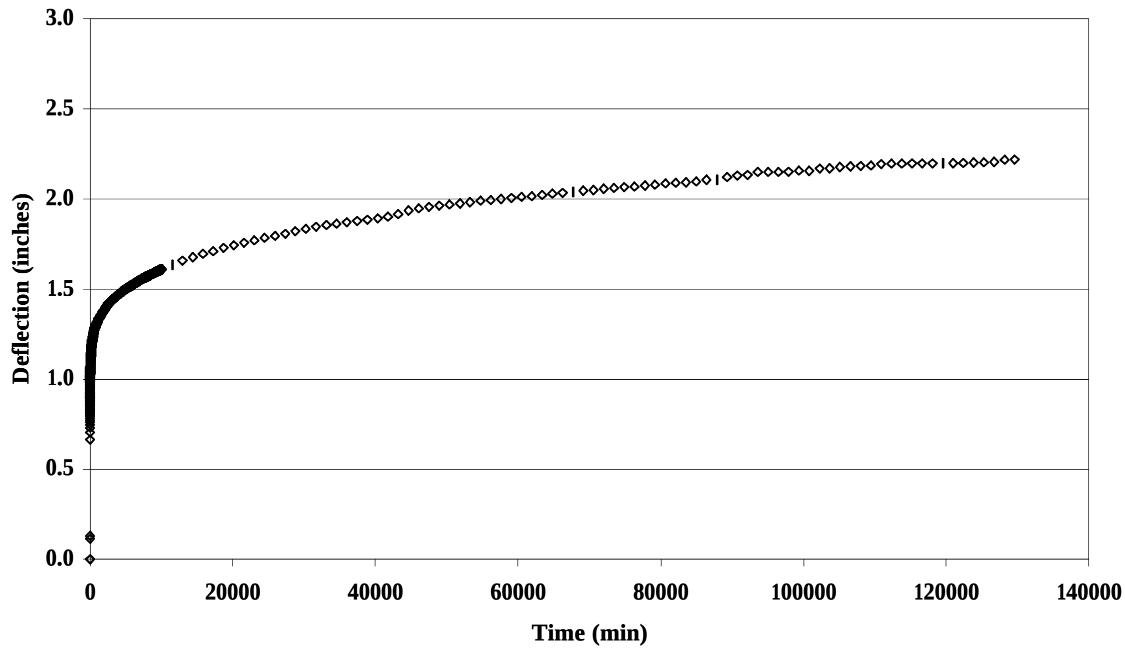
Deflection vs. Time at 60.0% of Ultimate
HDPE 8 Specimen # 16



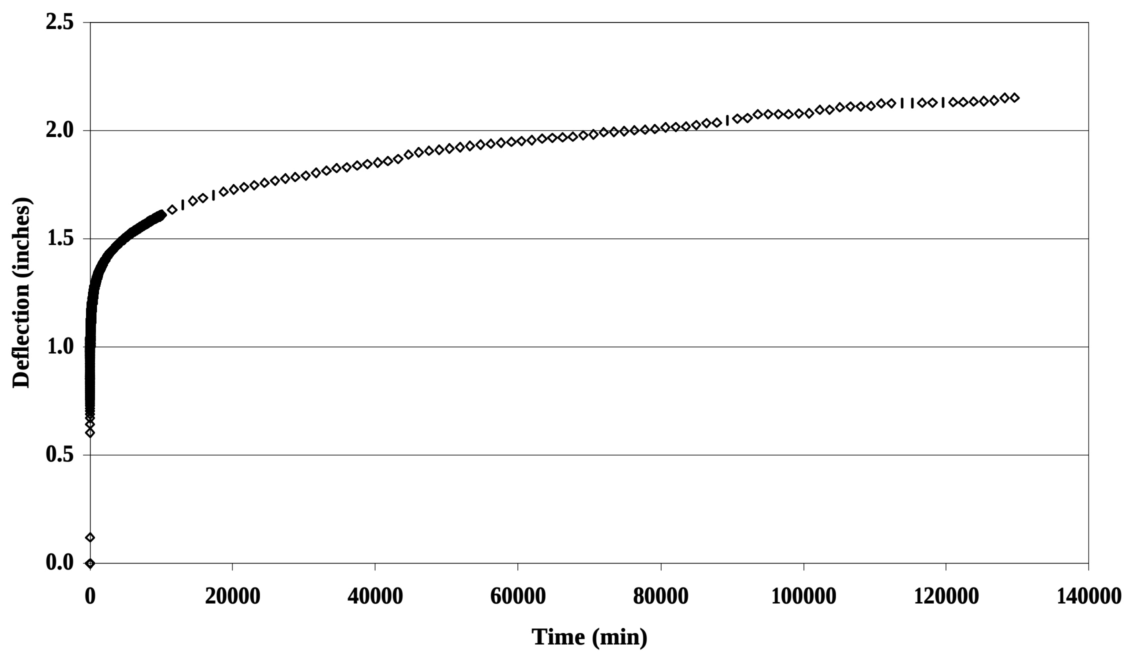
Deflection vs. Time at 42.9% of Ultimate
HDPE 8 Specimen # 5



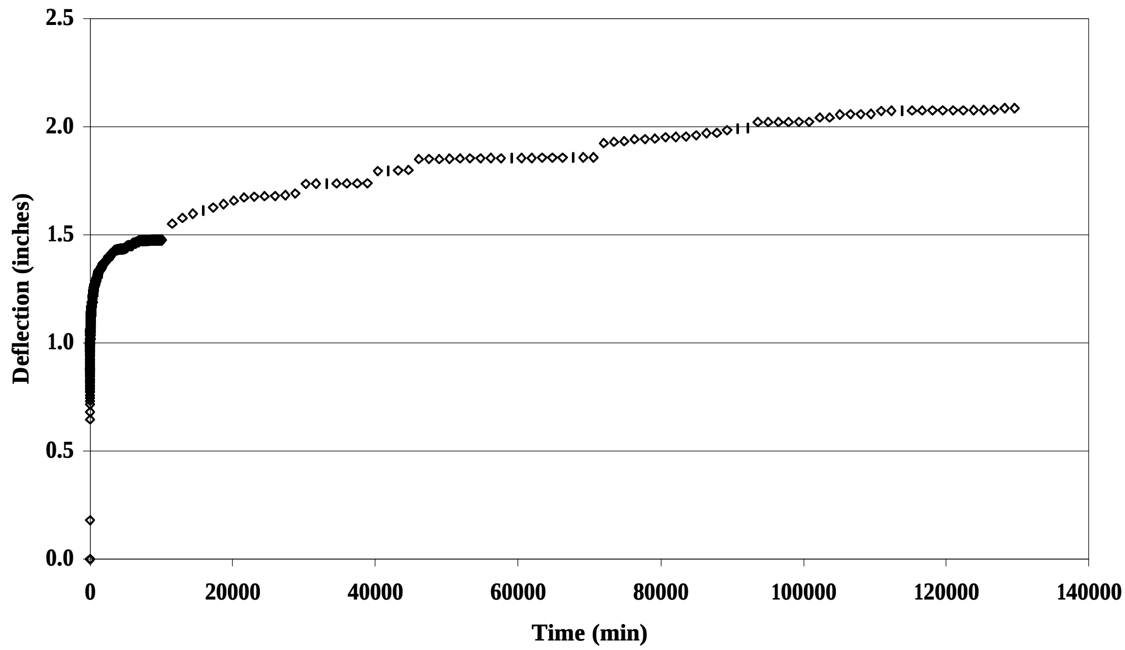
Deflection vs. Time at 42.9% of Ultimate
HDPE 8 Specimen # 30



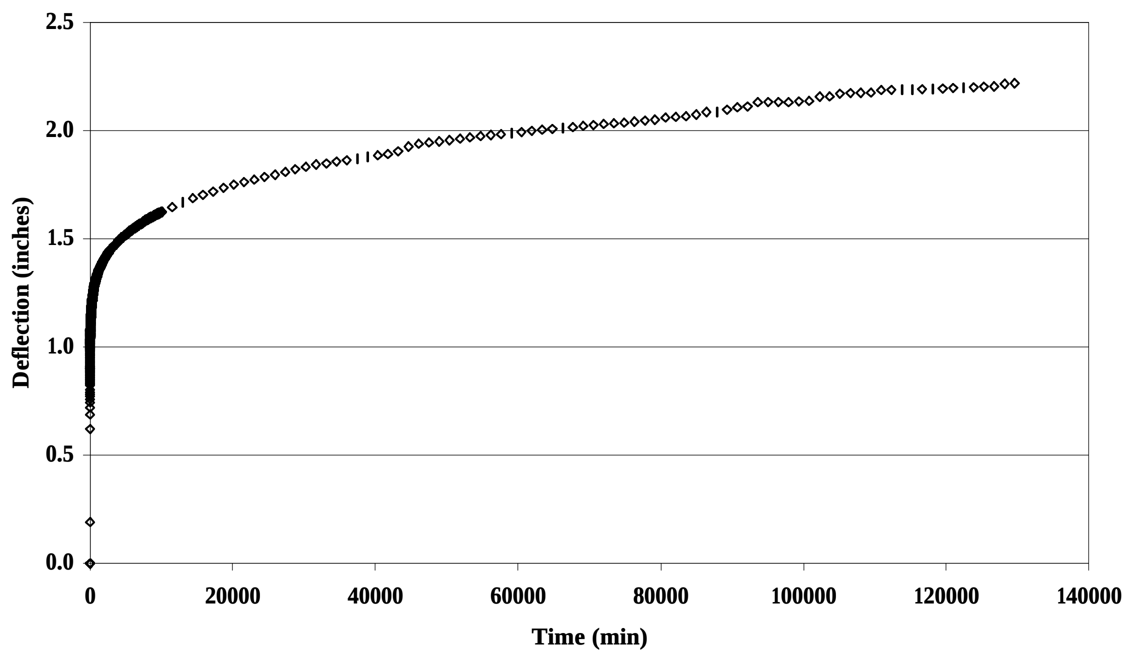
Deflection vs. Time at 42.9% of Ultimate
HDPE 8 Specimen # 53



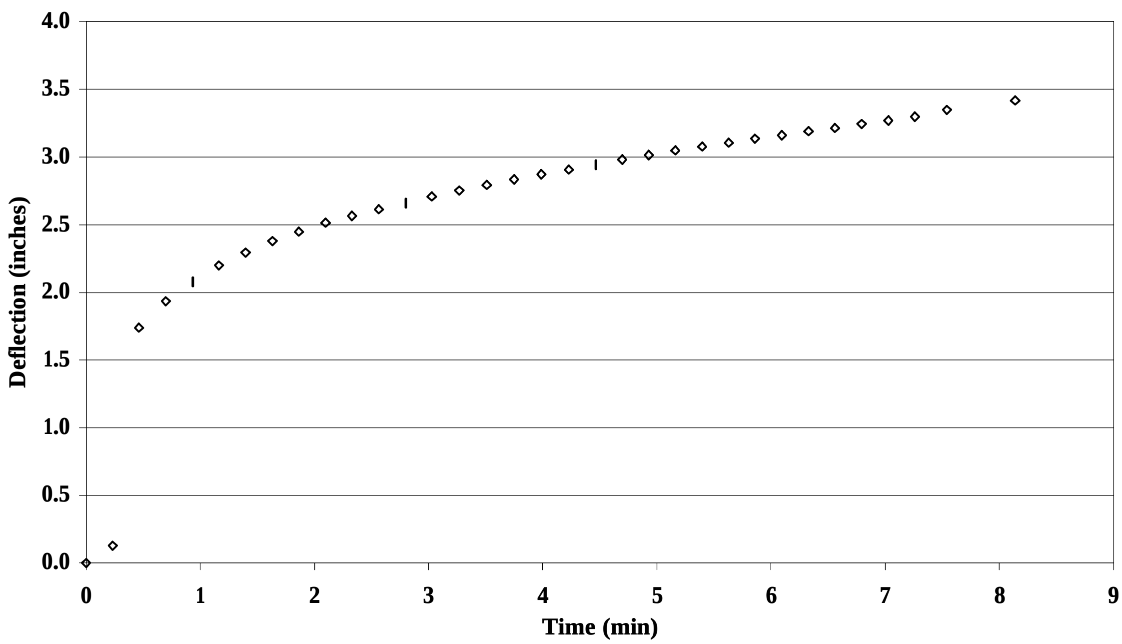
Deflection vs. Time at 42.9% of Ultimate
HDPE 8 Specimen # 23



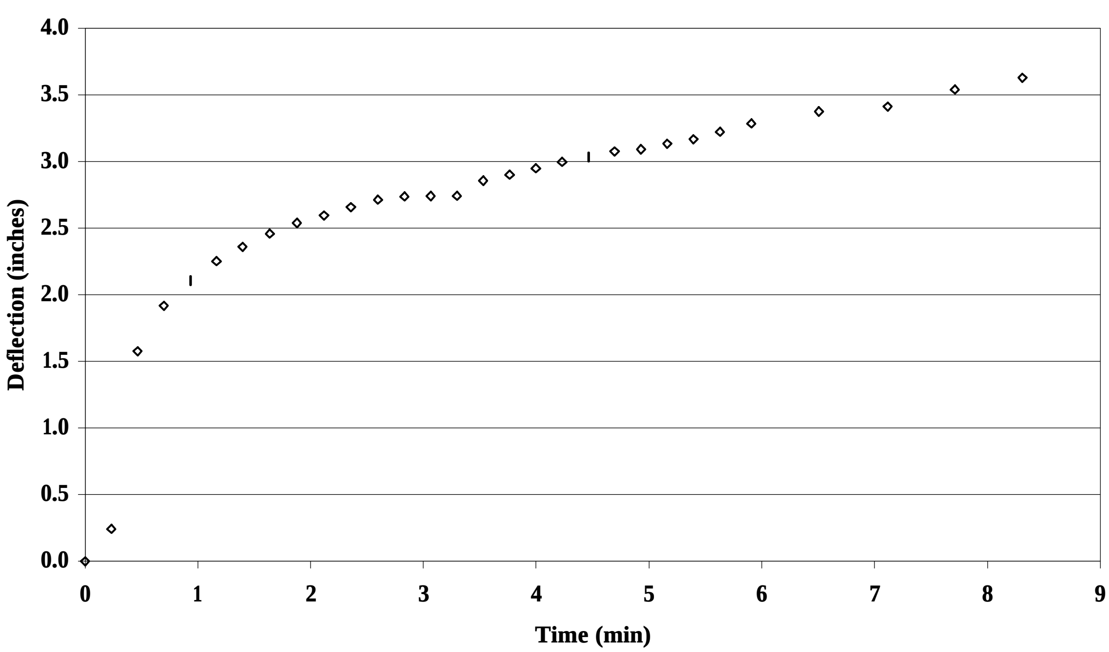
Deflection vs. Time at 42.9% of Ultimate
HDPE 8 Specimen # 49



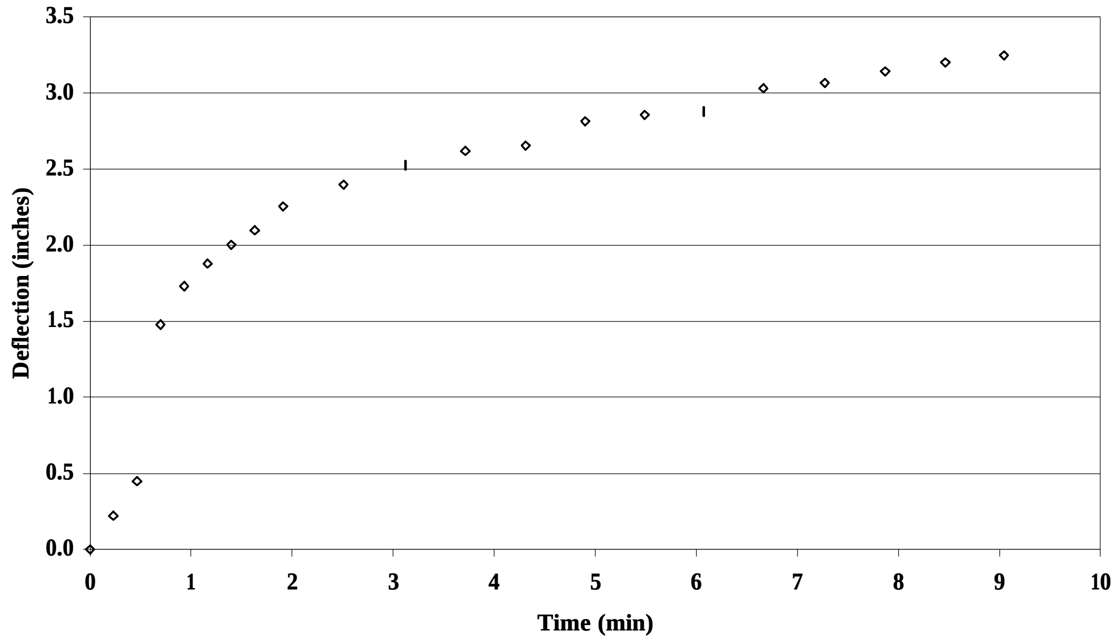
Deflection vs. Time at 79.0% of Ultimate
HDPE 67.5/32.5 Specimen # 64



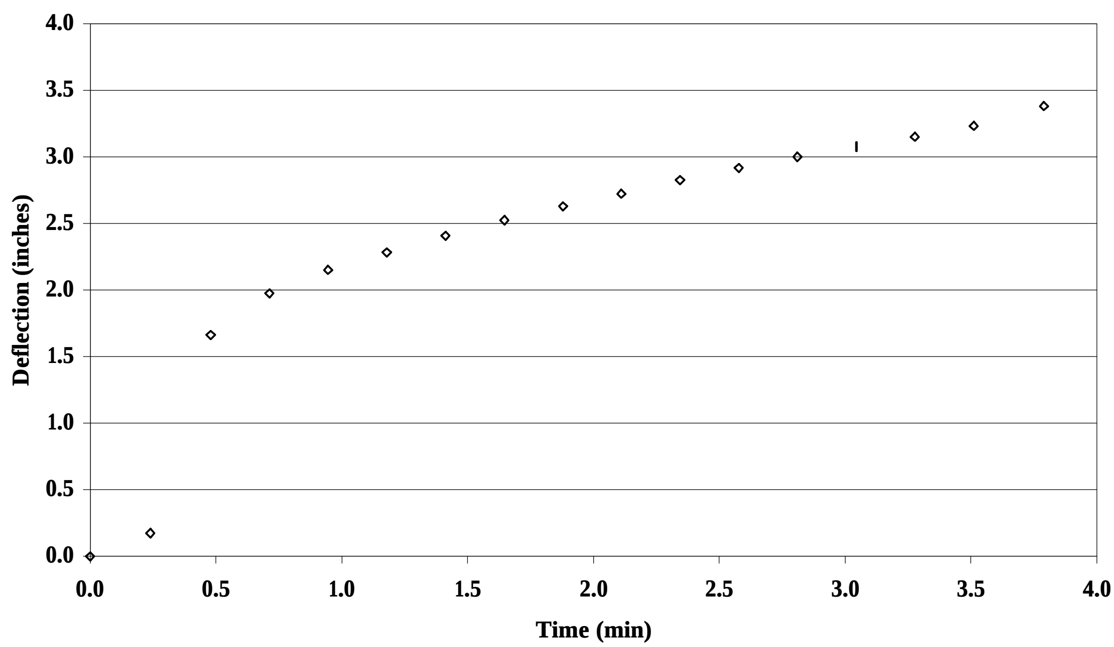
Deflection vs. Time at 79.0% of Ultimate
HDPE 67.5/32.5 Specimen # 32



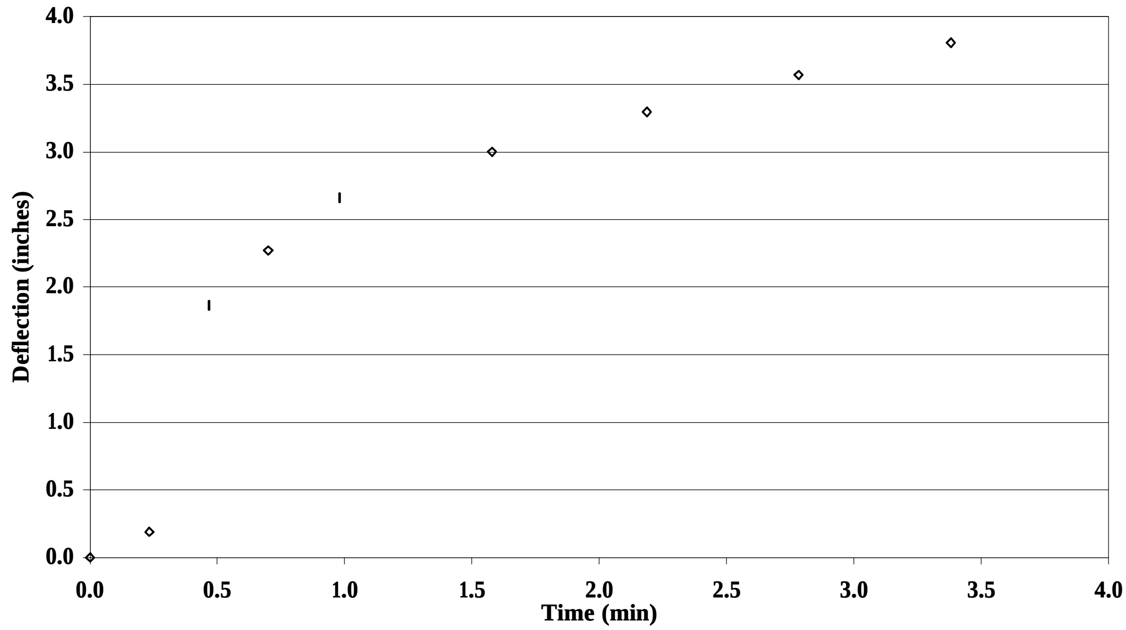
Deflection vs. Time at 79.0% of Ultimate
HDPE 67.5/32.5 Specimen # 44



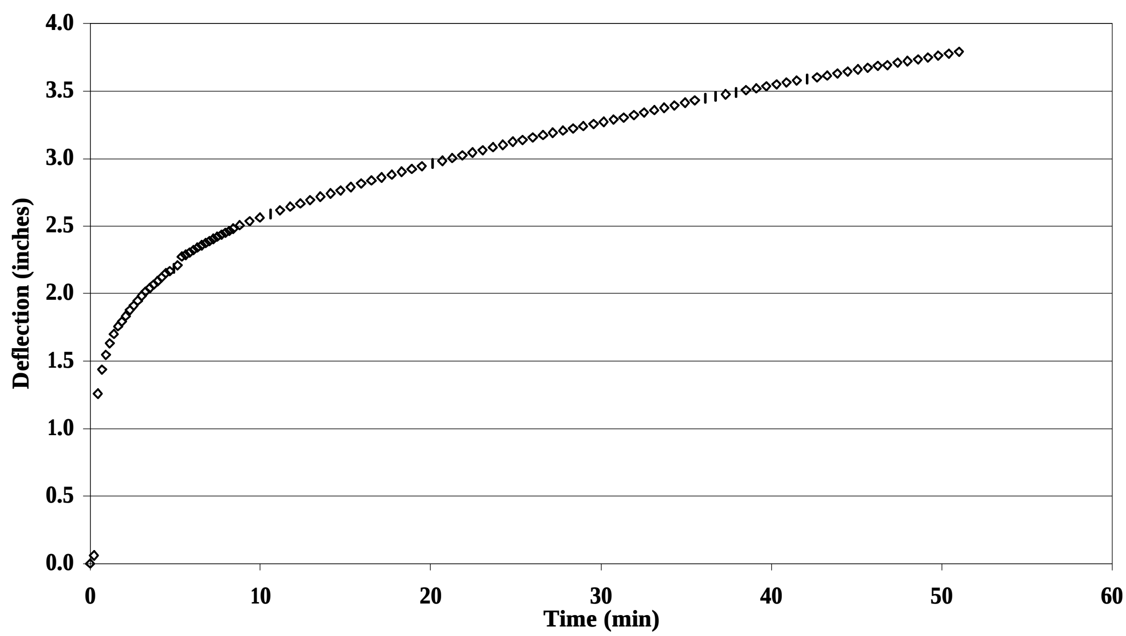
Deflection vs. Time at 79.0% of Ultimate
HDPE 67.5/32.5 Specimen # 74



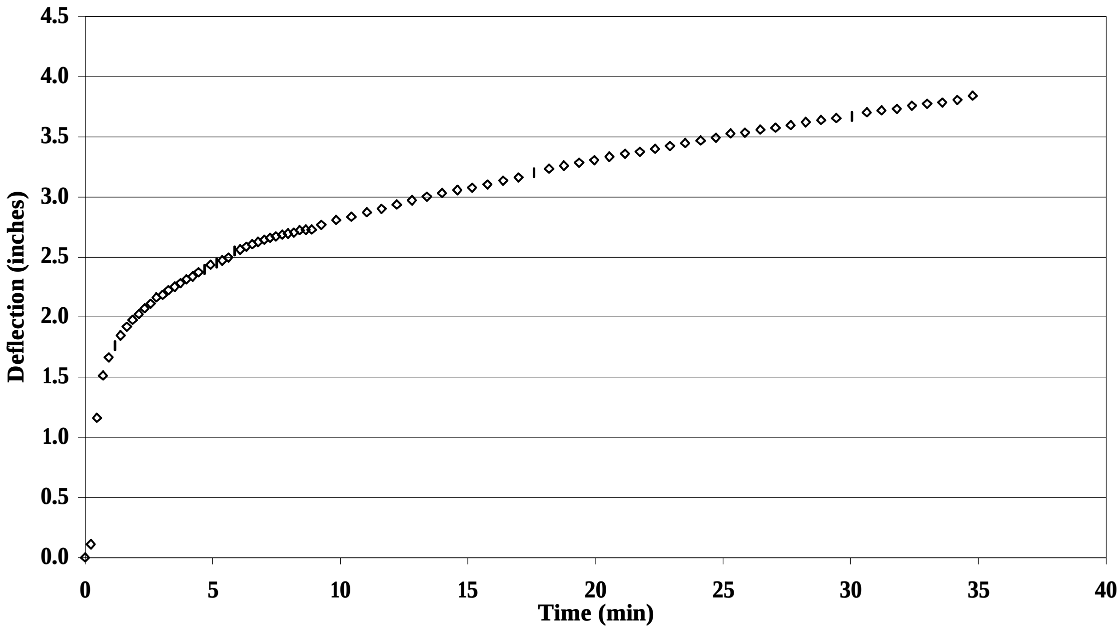
Deflection vs. Time at 79.0% of Ultimate
HDPE 67.5/32.5 Specimen # 71



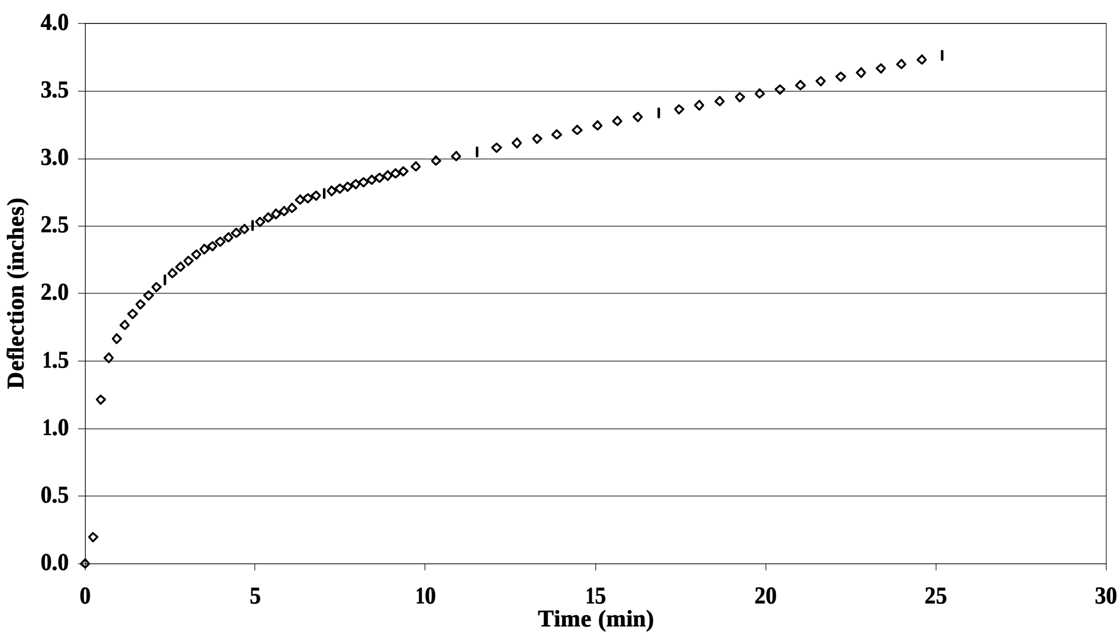
Deflection vs. Time at 74.9% of Ultimate
HDPE 67.5/32.5 Specimen # 65



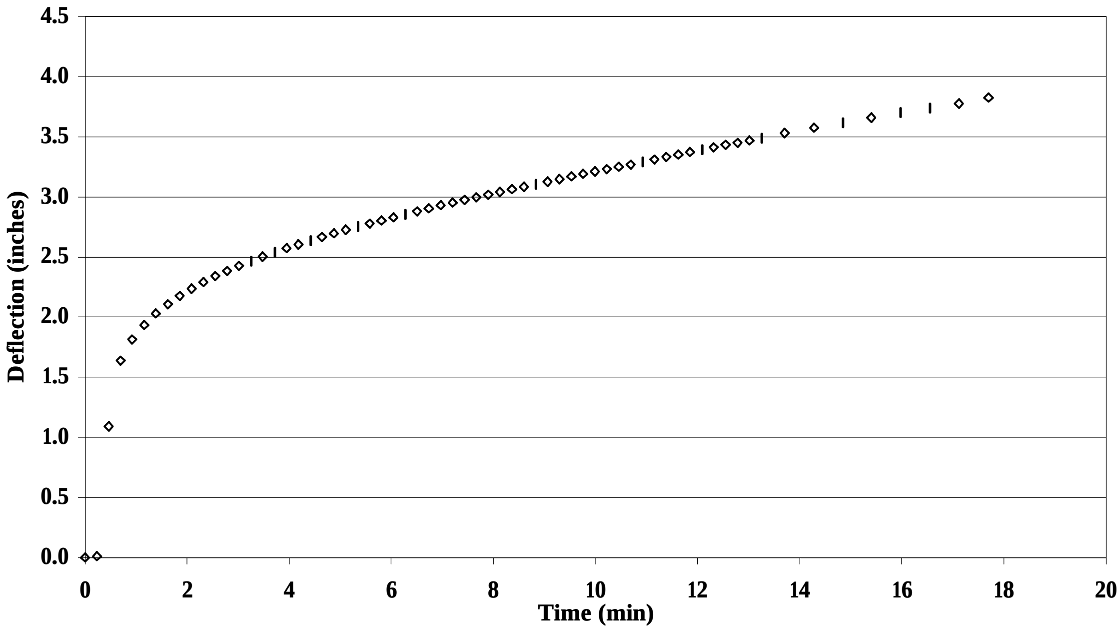
Deflection vs. Time at 74.9% of Ultimate
HDPE 67.5/32.5 Specimen # 73



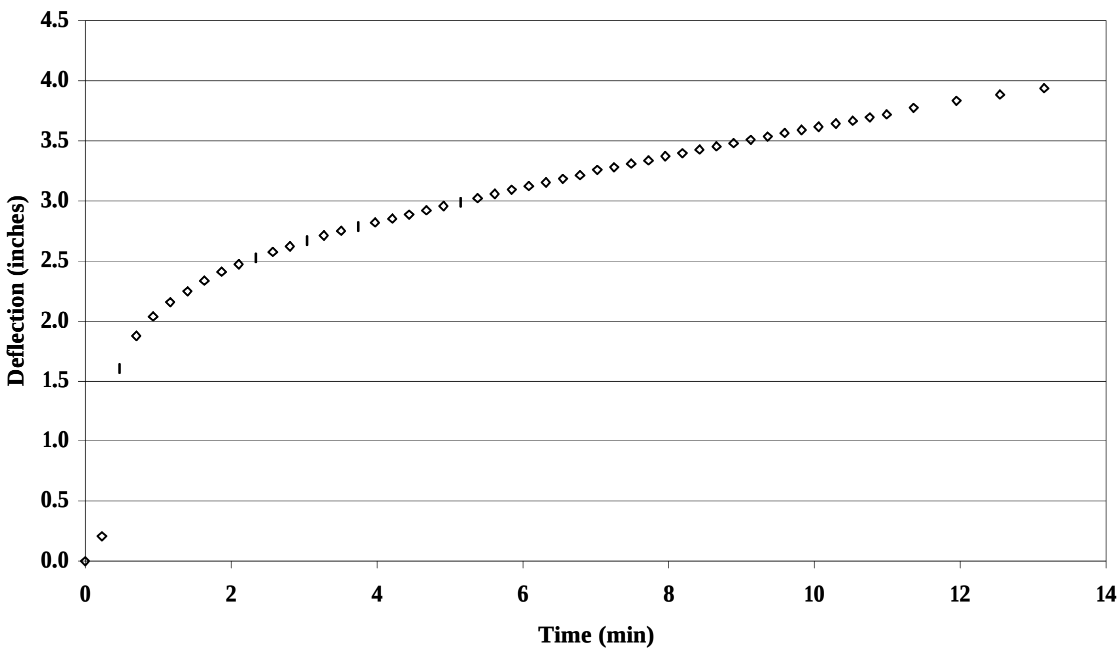
Deflection vs. Time at 74.9% of Ultimate
HDPE 67.5/32.5 Specimen # 33



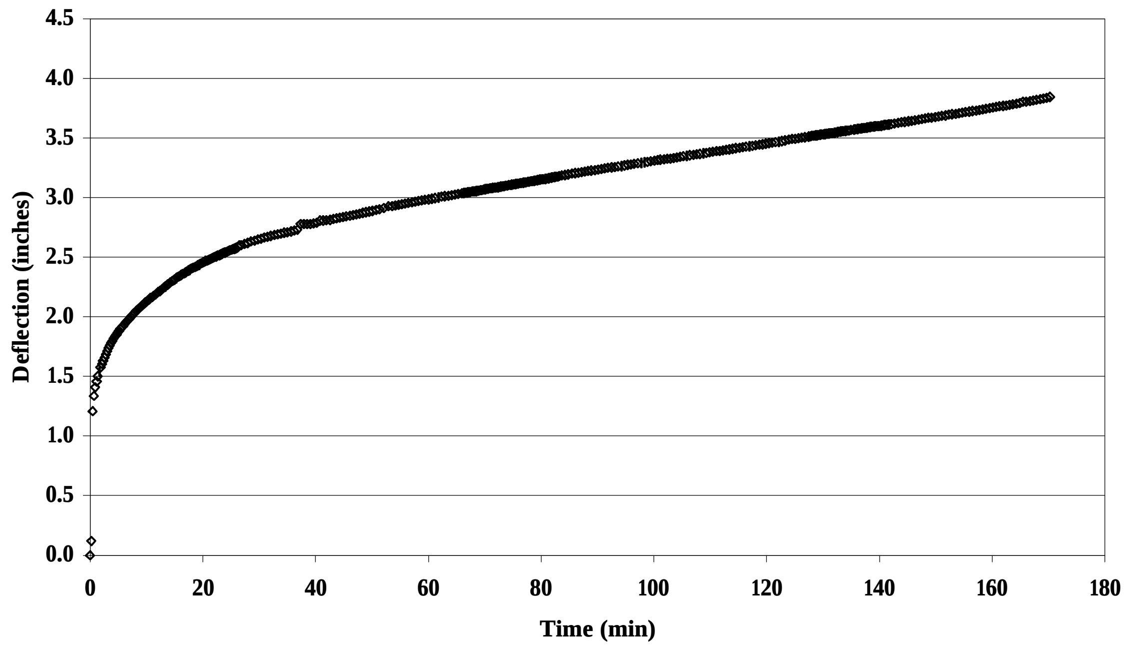
Deflection vs. Time at 74.9% of Ultimate
HDPE 67.5/32.5 Specimen # 77



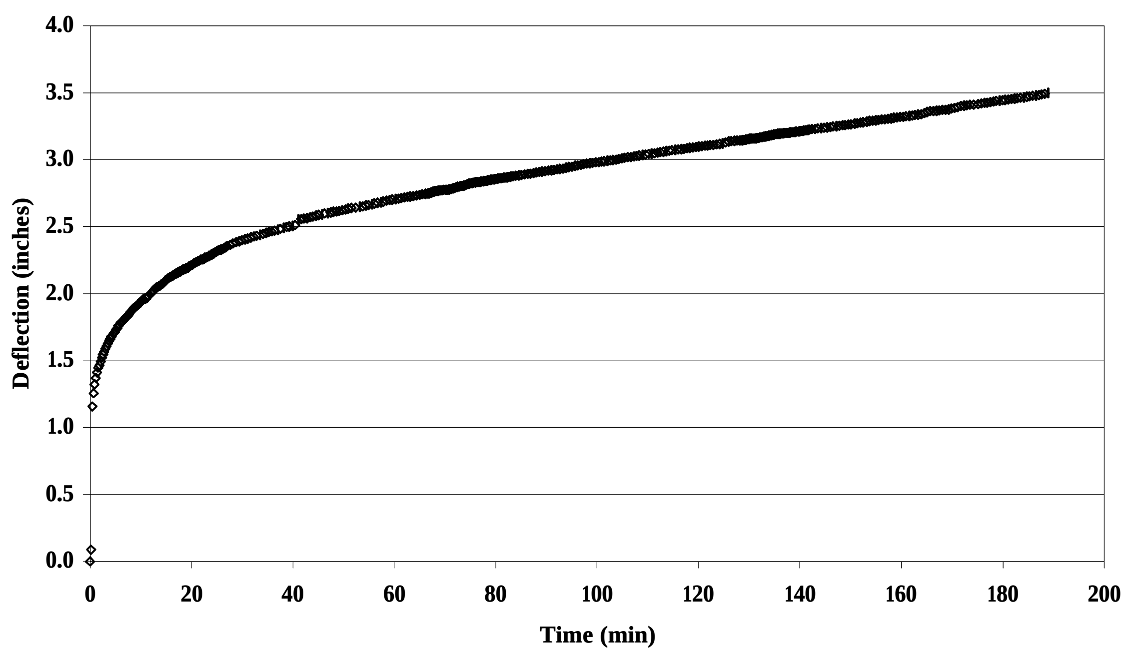
Deflection vs. Time at 74.9% of Ultimate
HDPE 67.5/32.5 Specimen # 75



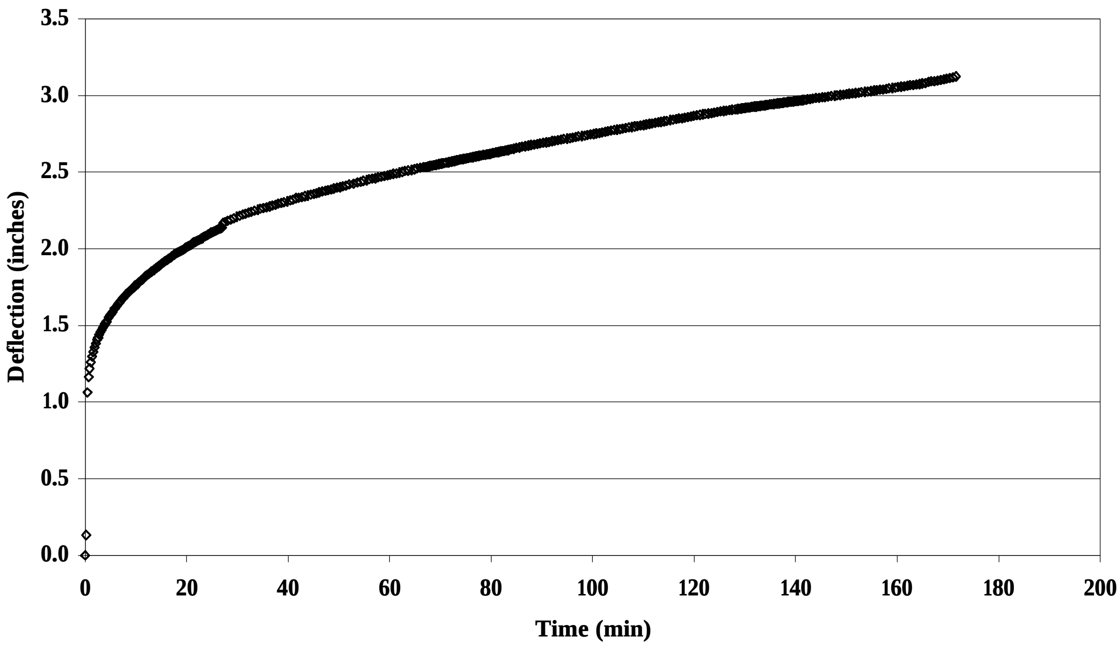
Deflection vs. Time at 66.6% of Ultimate
HDPE 67.5/32.5 Specimen # 82



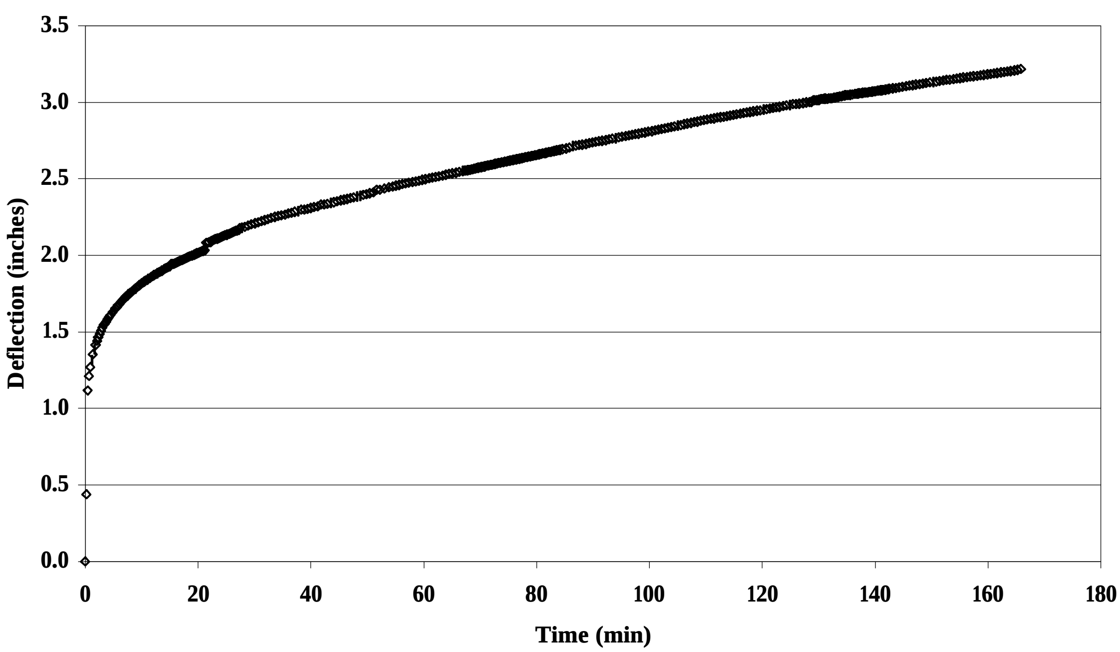
Deflection vs. Time at 66.6% of Ultimate
HDPE 67.5/32.5 Specimen # 45

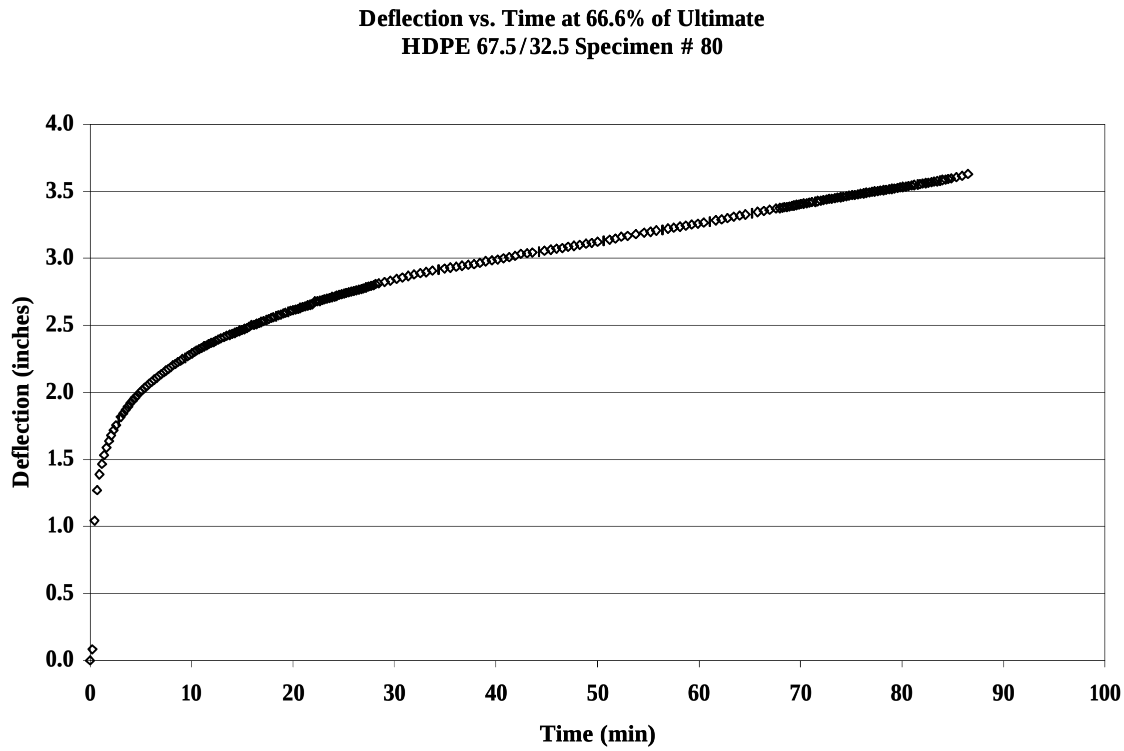


Deflection vs. Time at 66.6% of Ultimate
HDPE 67.5/32.5 Specimen # 83

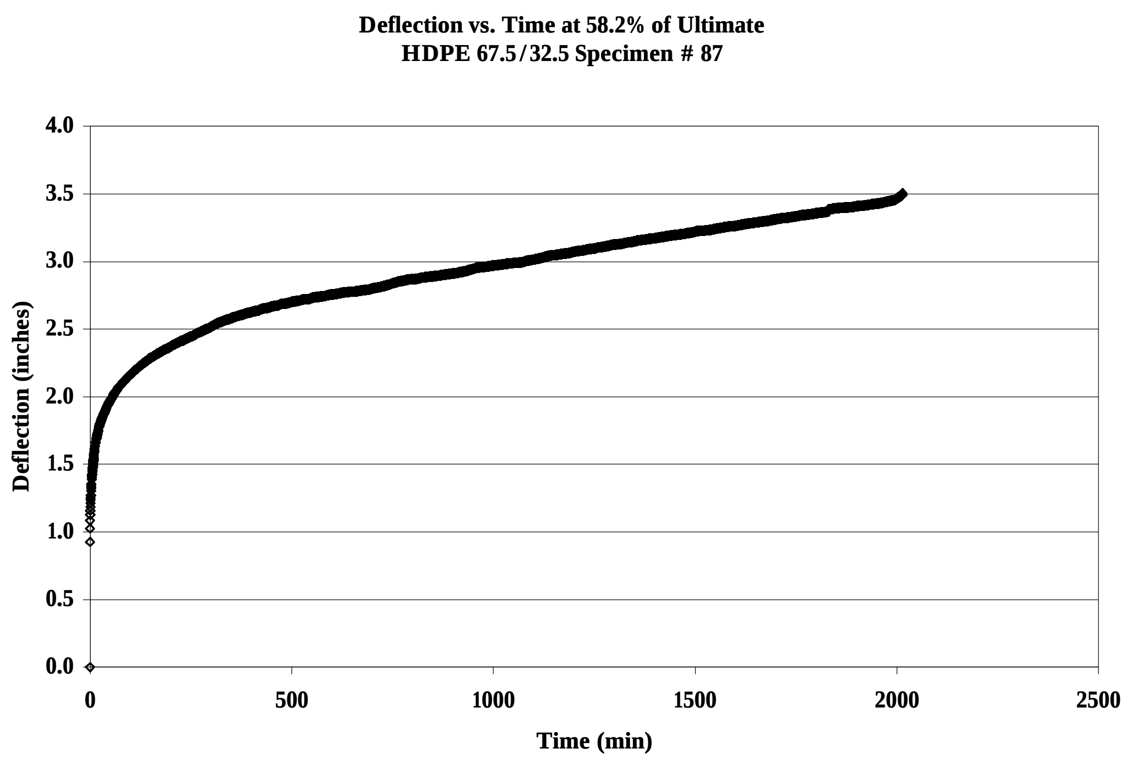


Deflection vs. Time at 66.6% of Ultimate
HDPE 67.5/32.5 Specimen # 84



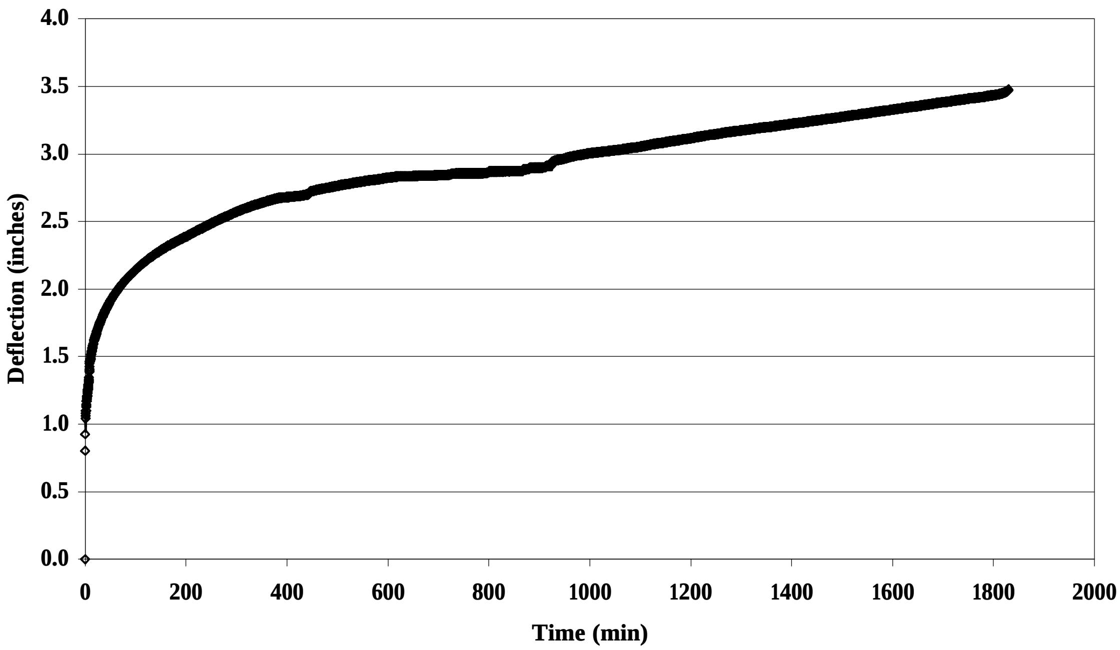


Deflection vs. Time at 66.6% of Ultimate
HDPE 67.5/32.5 Specimen # 80
Deflection (inches)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
60
70
80
90
100
Time (min)

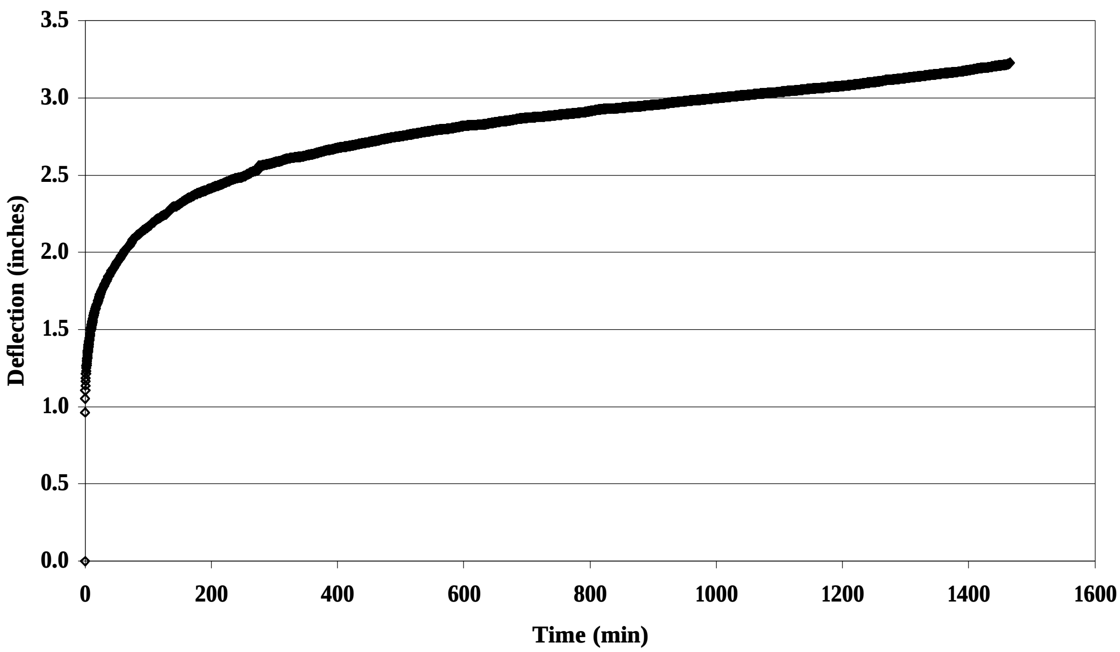


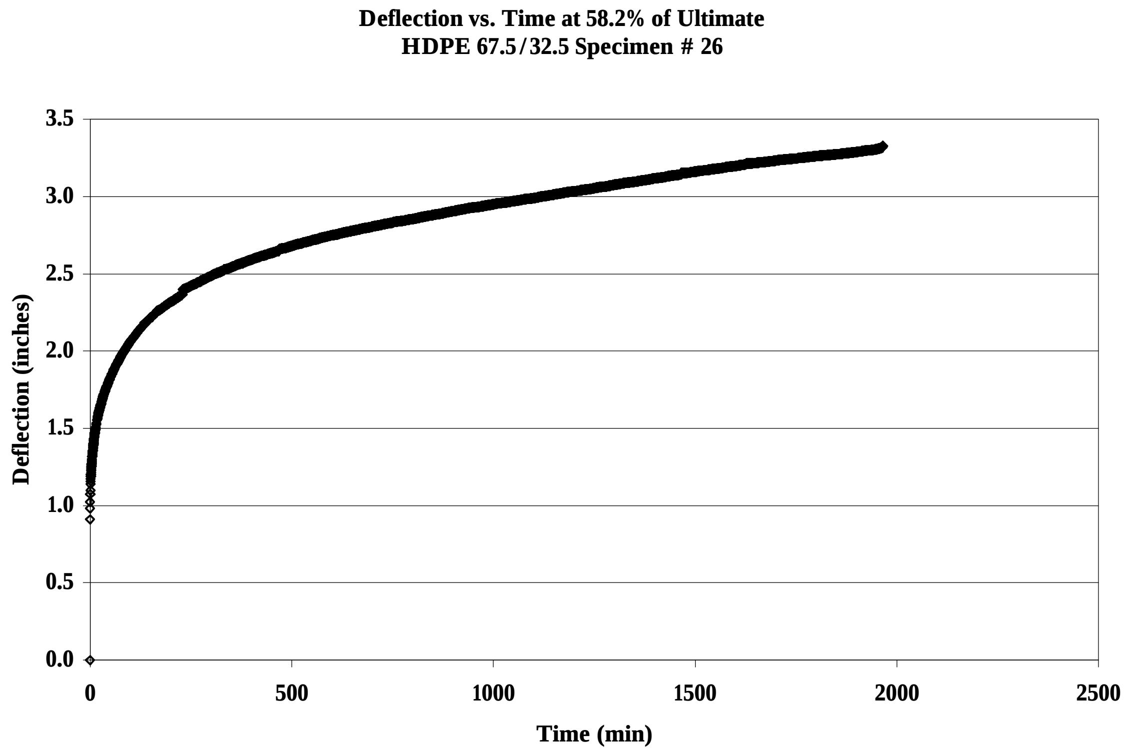
Deflection vs. Time at 58.2% of Ultimate
HDPE 67.5/32.5 Specimen # 87
Deflection (inches)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
500
1000
1500
2000
2500
Time (min)

Deflection vs. Time at 58.2% of Ultimate
HDPE 67.5/32.5 Specimen # 88

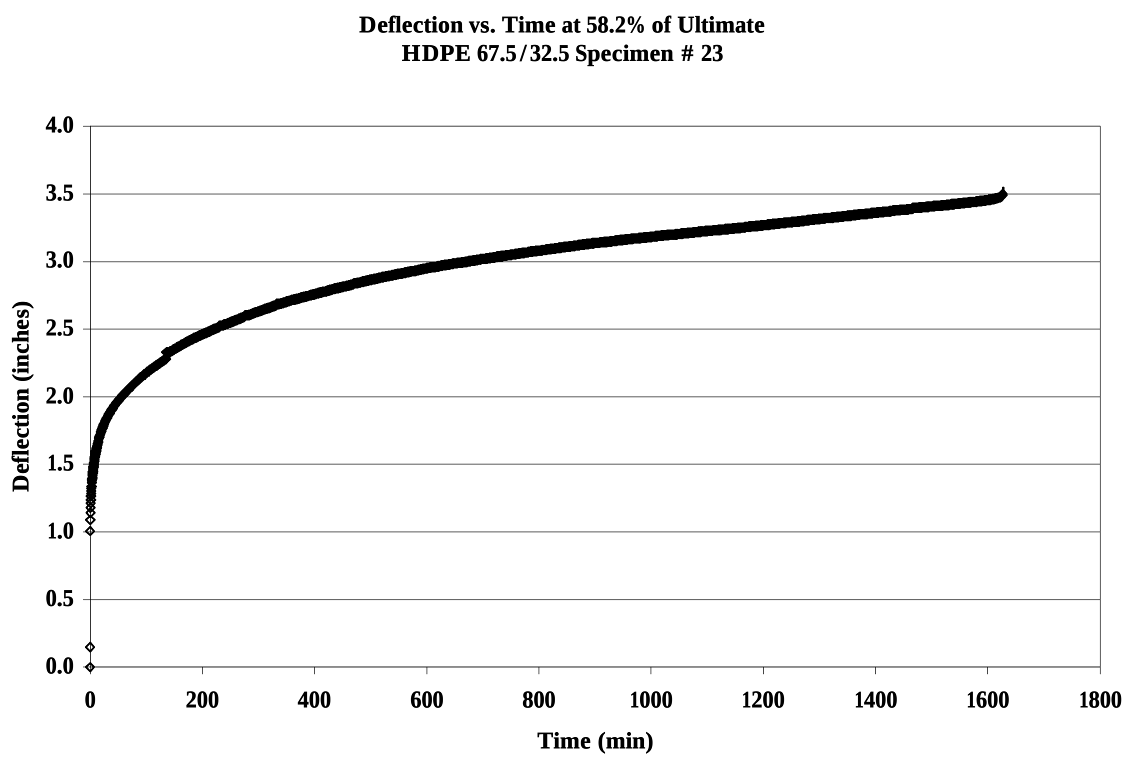


Deflection vs. Time at 58.2% of Ultimate
HDPE 67.5/32.5 Specimen # 24

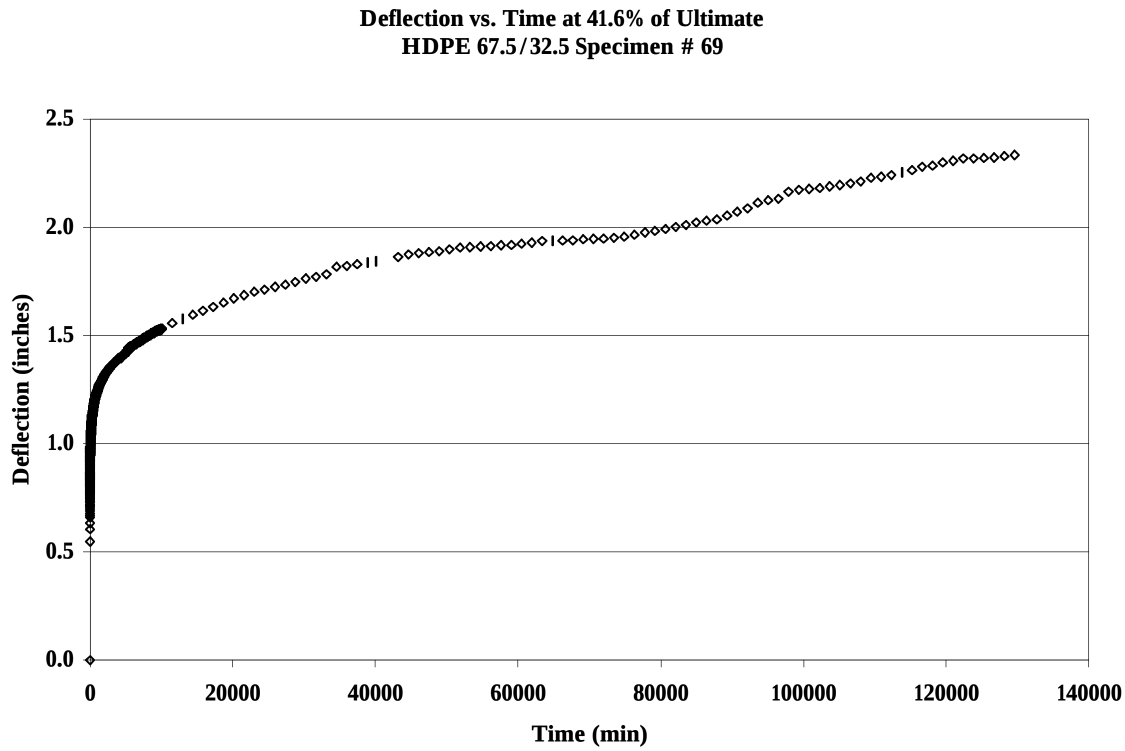


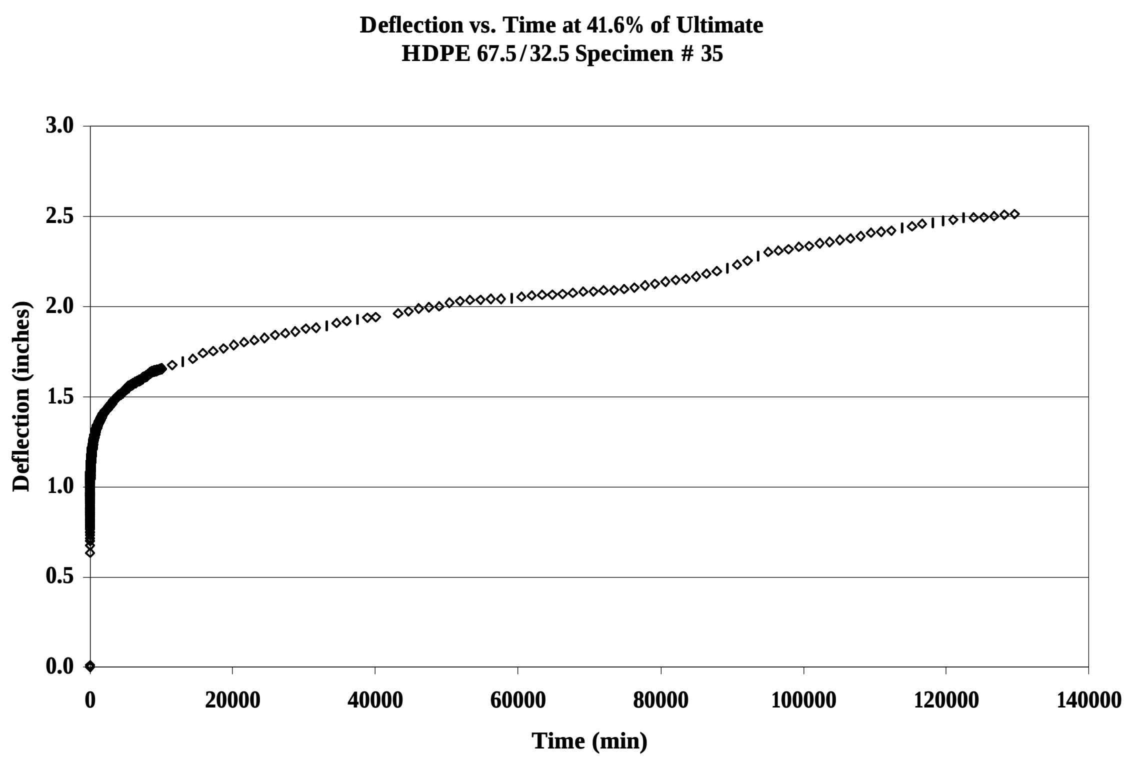


Deflection vs. Time at 58.2% of Ultimate
HDPE 67.5/32.5 Specimen # 26
Deflection (inches)
Time (min)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
500
1000
1500
2000
2500

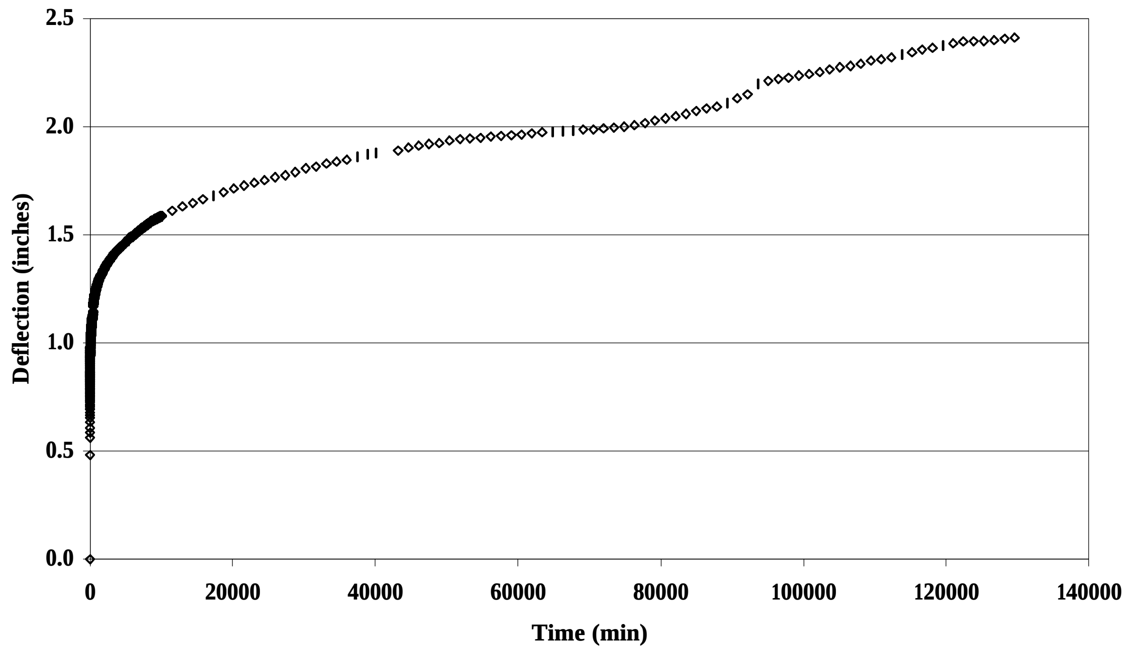


Deflection vs. Time at 58.2% of Ultimate
HDPE 67.5/32.5 Specimen # 23
Deflection (inches)
Time (min)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0
200
400
600
800
1000
1200
1400
1600
1800

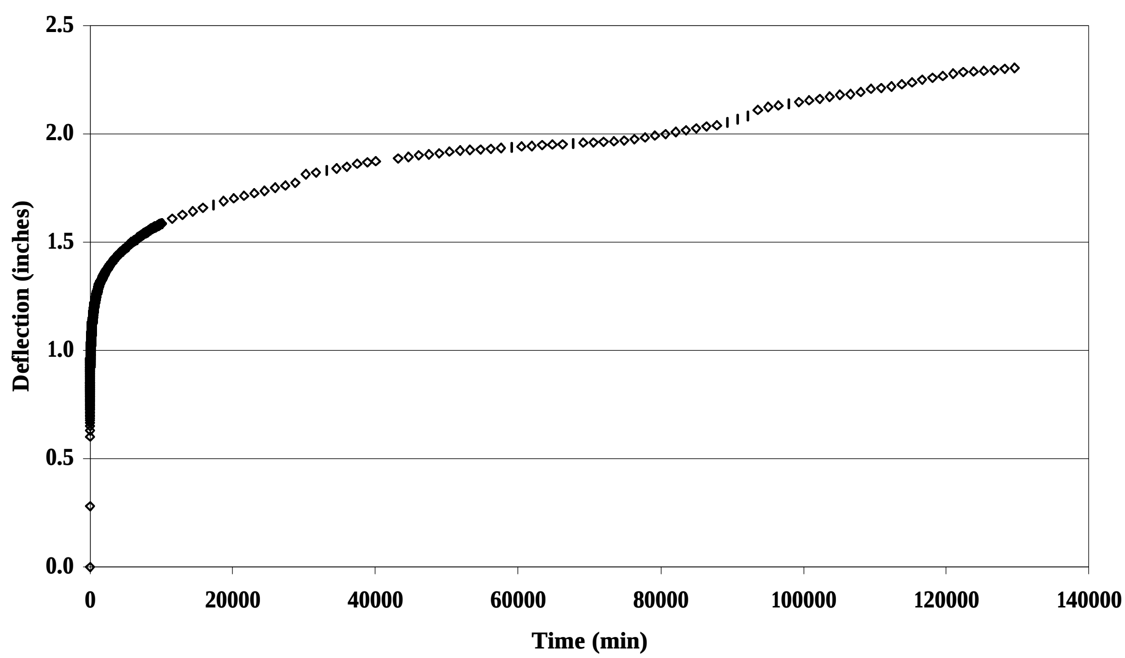

Deflection vs. Time at 41.6% of Ultimate
HDPE 67.5/32.5 Specimen # 69
Deflection (inches)
0.0
0.5
1.0
1.5
2.0
2.5
0
20000
40000
60000
80000
100000
120000
140000
Time (min)

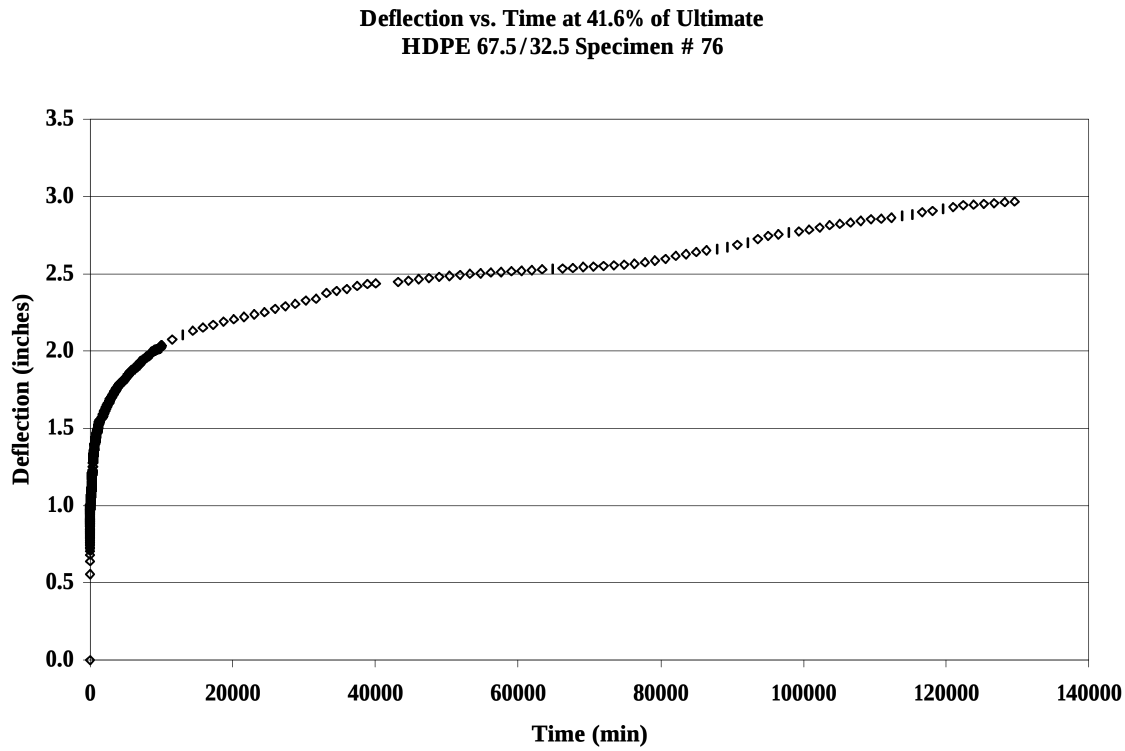

Deflection vs. Time at 41.6% of Ultimate
HDPE 67.5/32.5 Specimen # 35
Deflection (inches)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
20000
40000
60000
80000
100000
120000
140000
Time (min)

Deflection vs. Time at 41.6% of Ultimate
HDPE 67.5/32.5 Specimen # 81

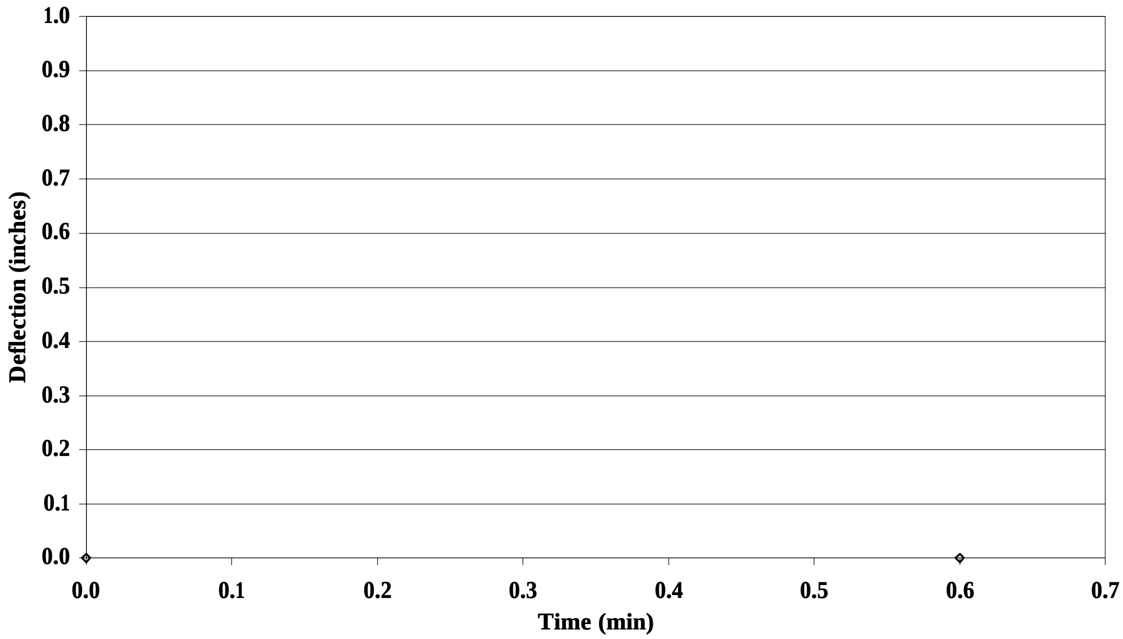


Deflection vs. Time at 41.6% of Ultimate
HDPE 67.5/32.5 Specimen # 63

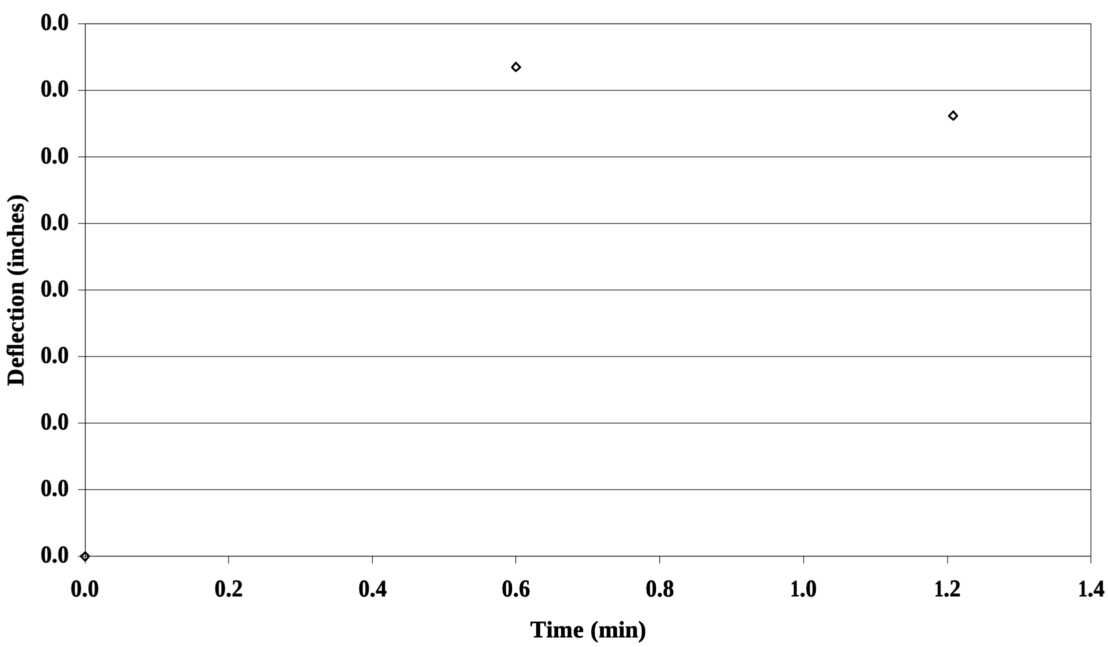



Deflection vs. Time at 41.6% of Ultimate
HDPE 67.5/32.5 Specimen # 76
Deflection (inches)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
20000
40000
60000
80000
100000
120000
140000
Time (min)

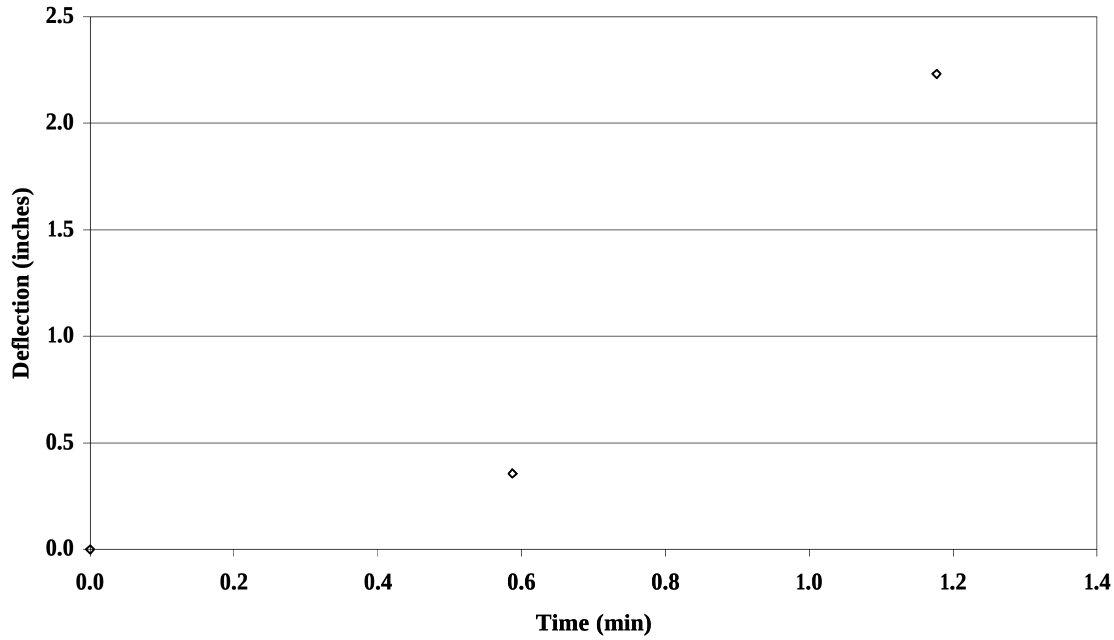
Deflection vs. Time at 86.9% of Ultimate
HDPE w/ MAPE Specimen # 73



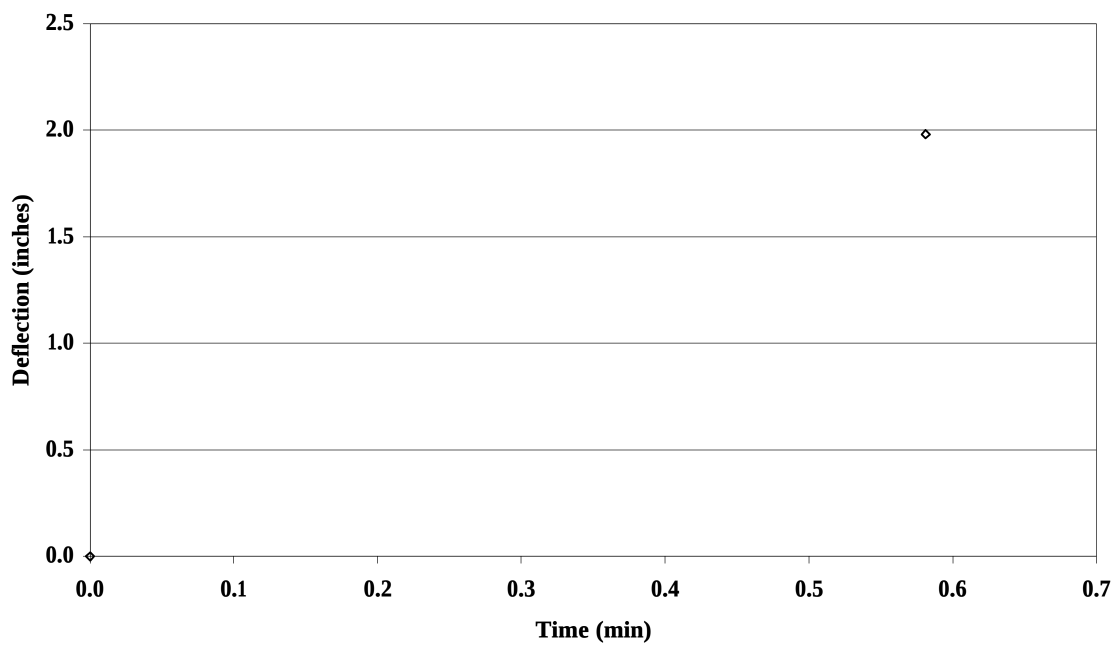
Deflection vs. Time at 86.9% of Ultimate
HDPE w/ MAPE Specimen # 53



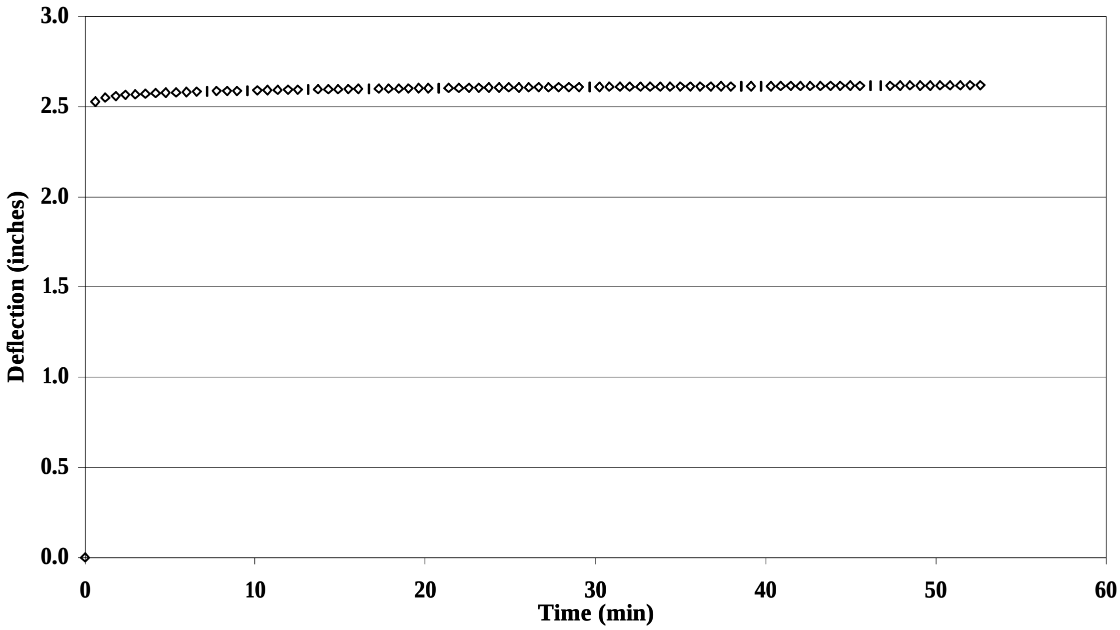
Deflection vs. Time at 86.9% of Ultimate
HDPE w/ MAPE Specimen # 21



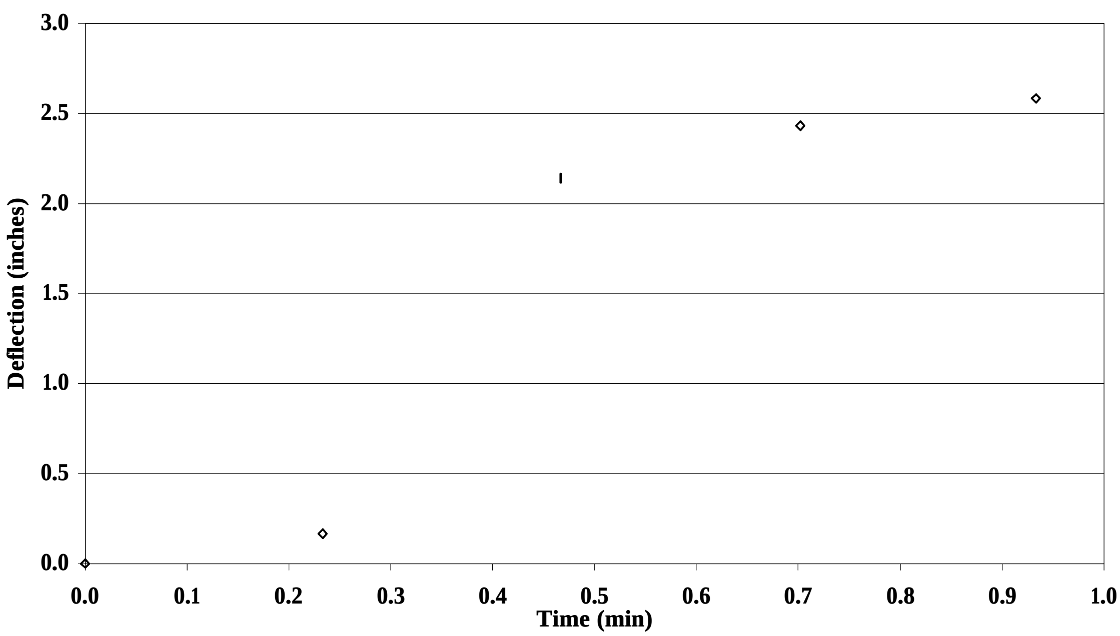
Deflection vs. Time at 86.9% of Ultimate
HDPE w/ MAPE Specimen # 33

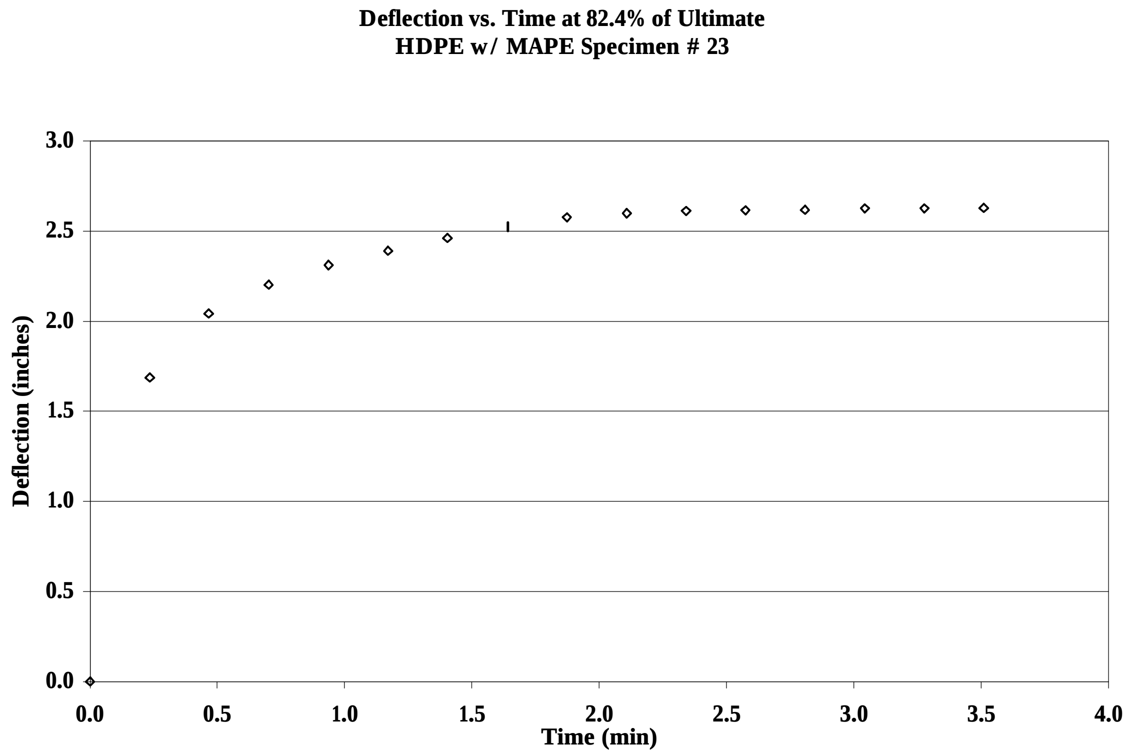


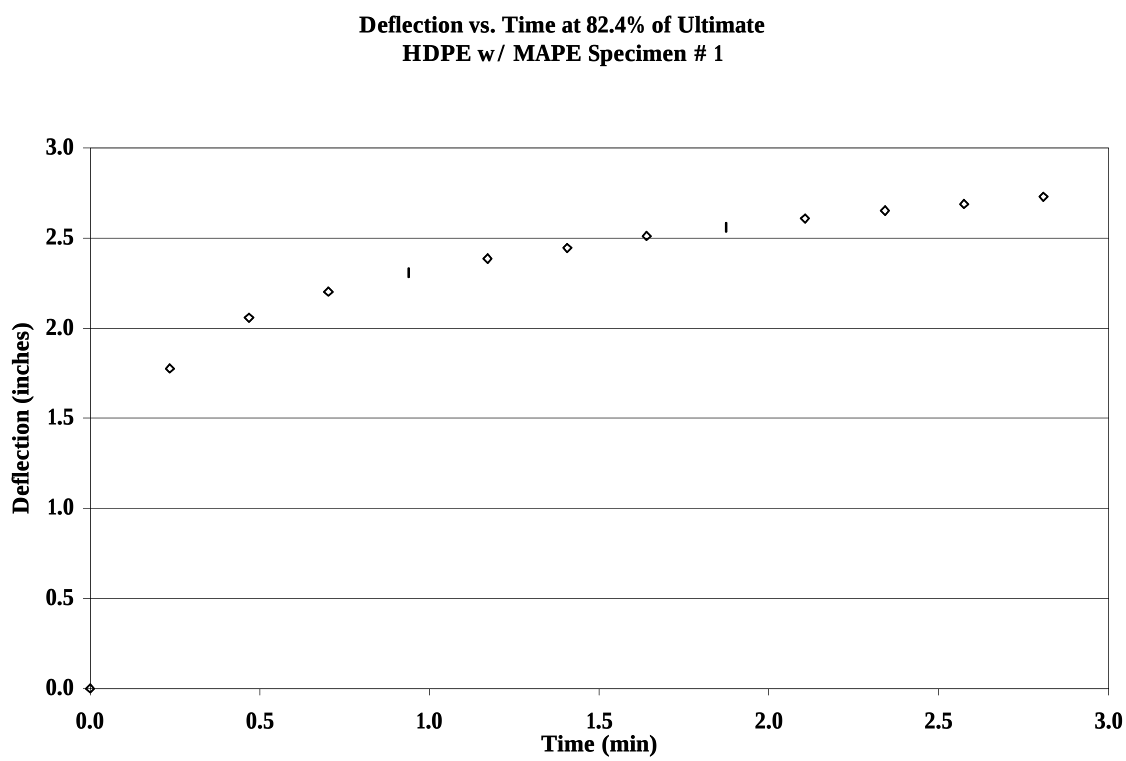
Deflection vs. Time at 86.9% of Ultimate
HDPE w/ MAPE Specimen # 13



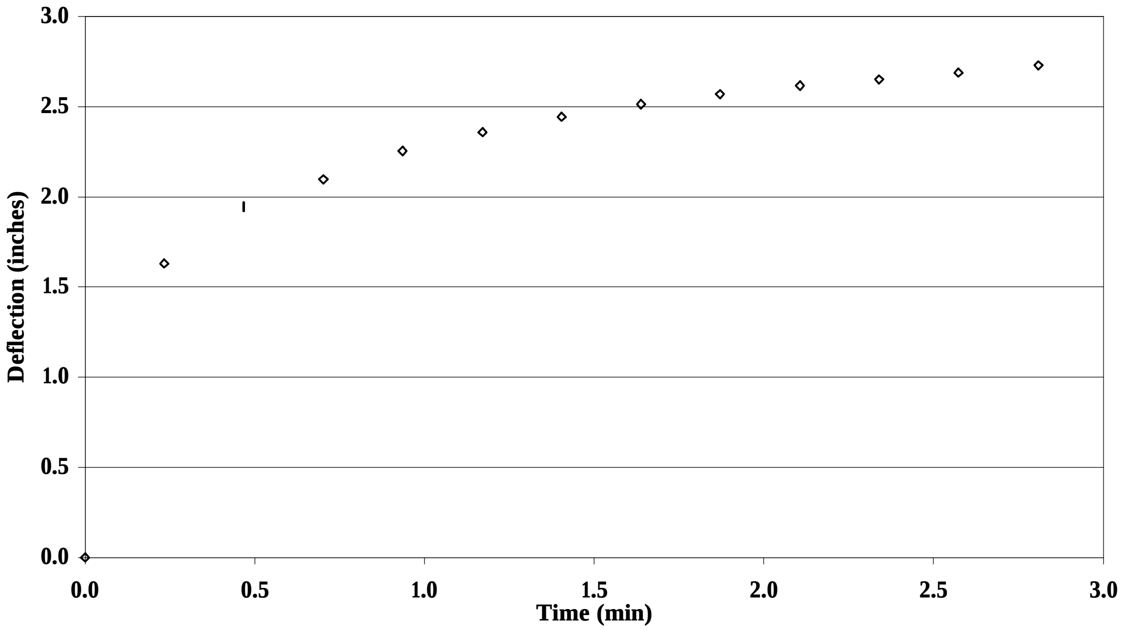
Deflection vs. Time at 82.4% of Ultimate
HDPE w/ MAPE Specimen # 3



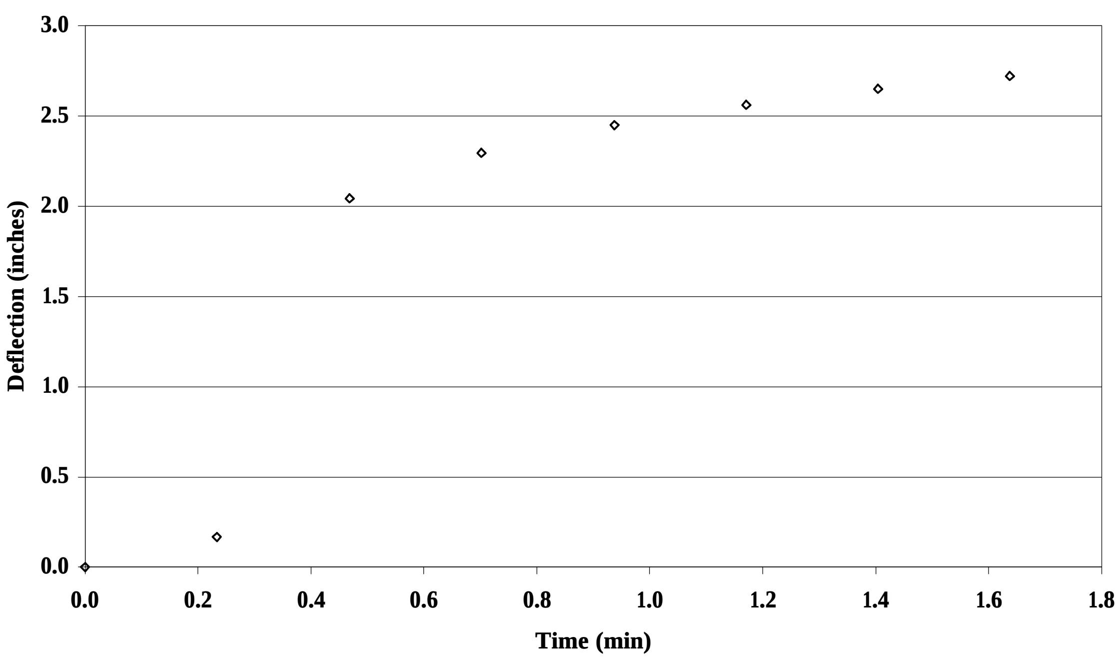

Deflection vs. Time at 82.4% of Ultimate
HDPE w/ MAPE Specimen # 23
Deflection (inches)
Time (min)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0


Deflection vs. Time at 82.4% of Ultimate
HDPE w/ MAPE Specimen # 1
Deflection (inches)
Time (min)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0

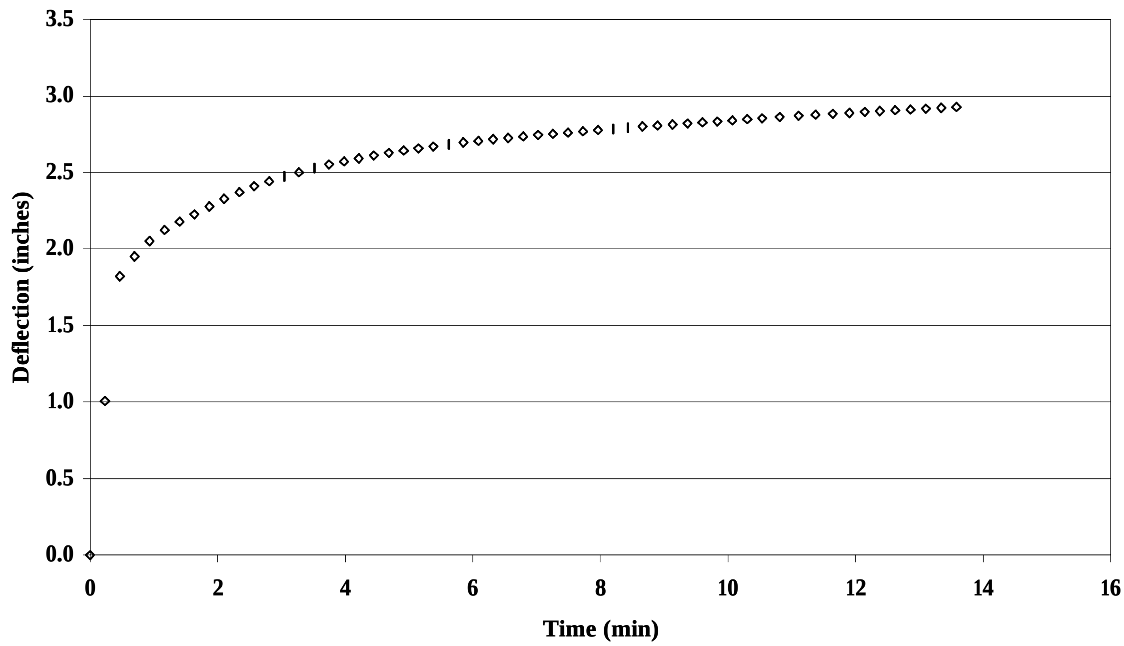
Deflection vs. Time at 82.4% of Ultimate
HDPE w/ MAPE Specimen # 43



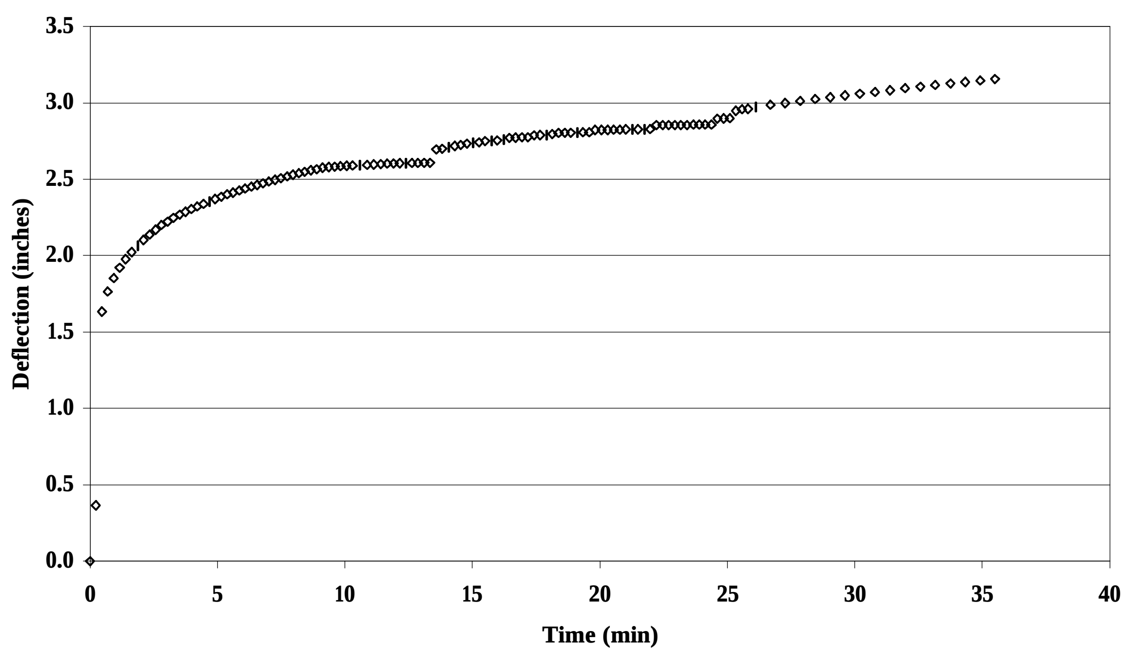
Deflection vs. Time at 82.4% of Ultimate
HDPE w/ MAPE Specimen # 63



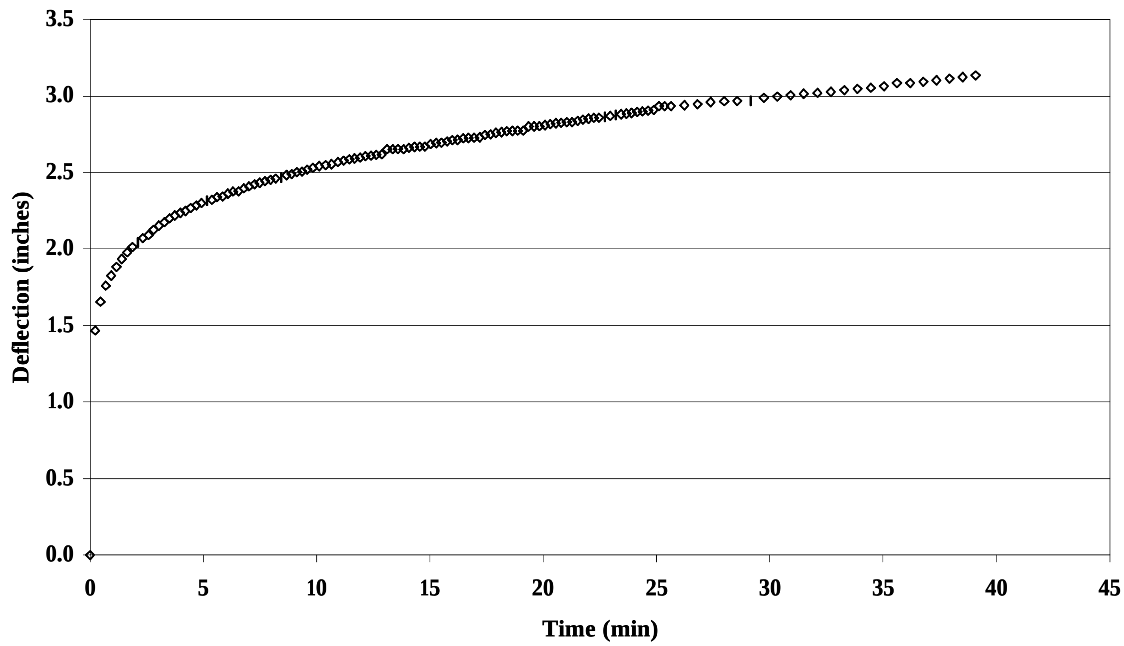
Deflection vs. Time at 73.2% of Ultimate
HDPE w/ MAPE Specimen # 11



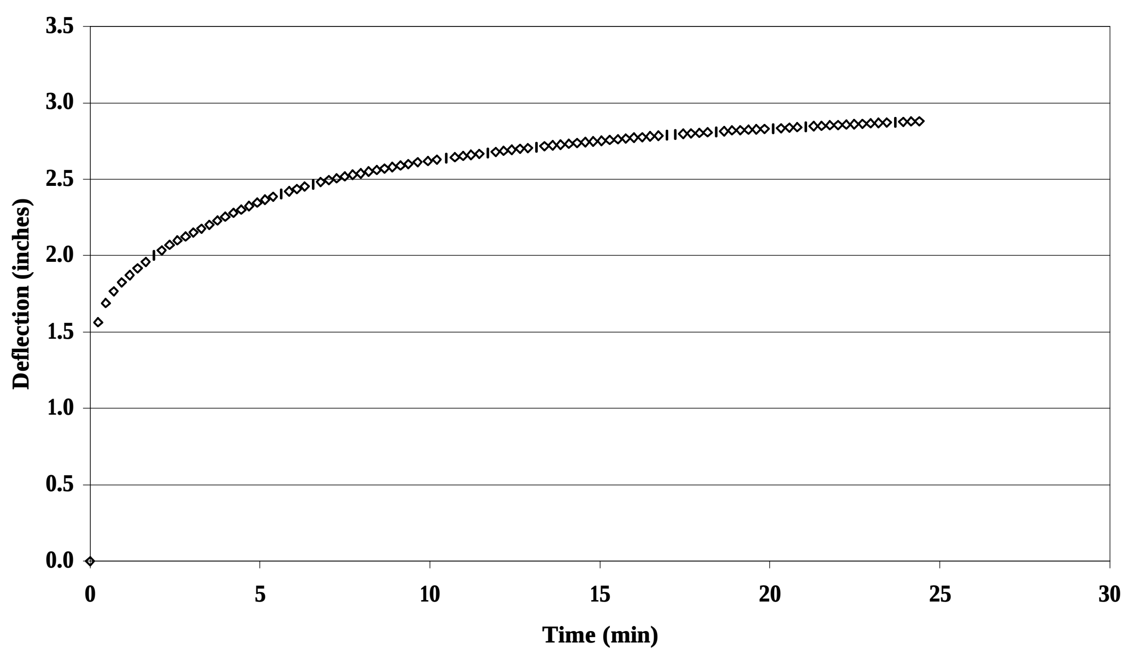
Deflection vs. Time at 73.2% of Ultimate
HDPE w/ MAPE Specimen # 14

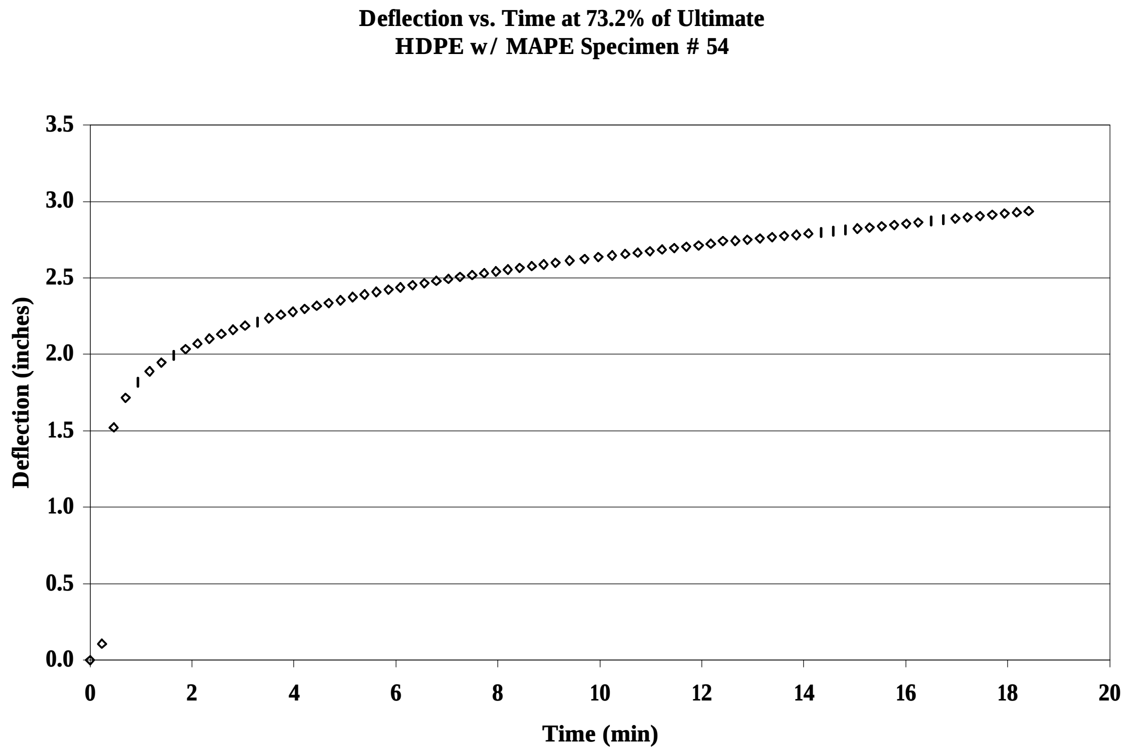


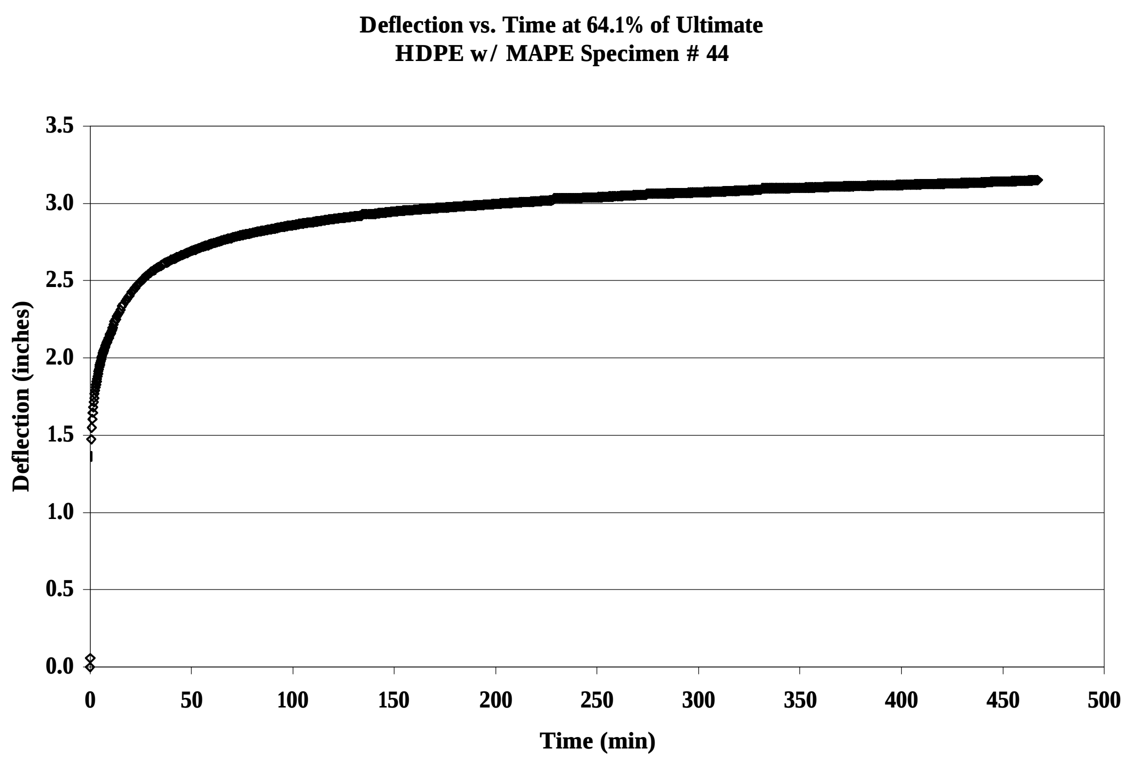
Deflection vs. Time at 73.2% of Ultimate
HDPE w/ MAPE Specimen # 34



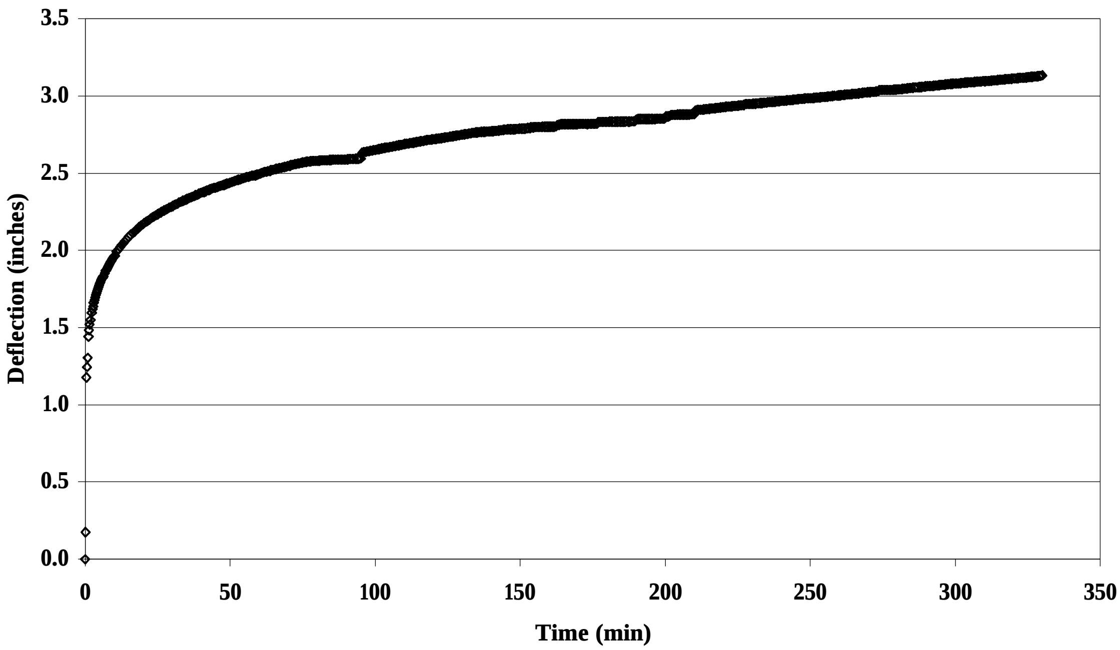
Deflection vs. Time at 73.2% of Ultimate
HDPE w/ MAPE Specimen # 41



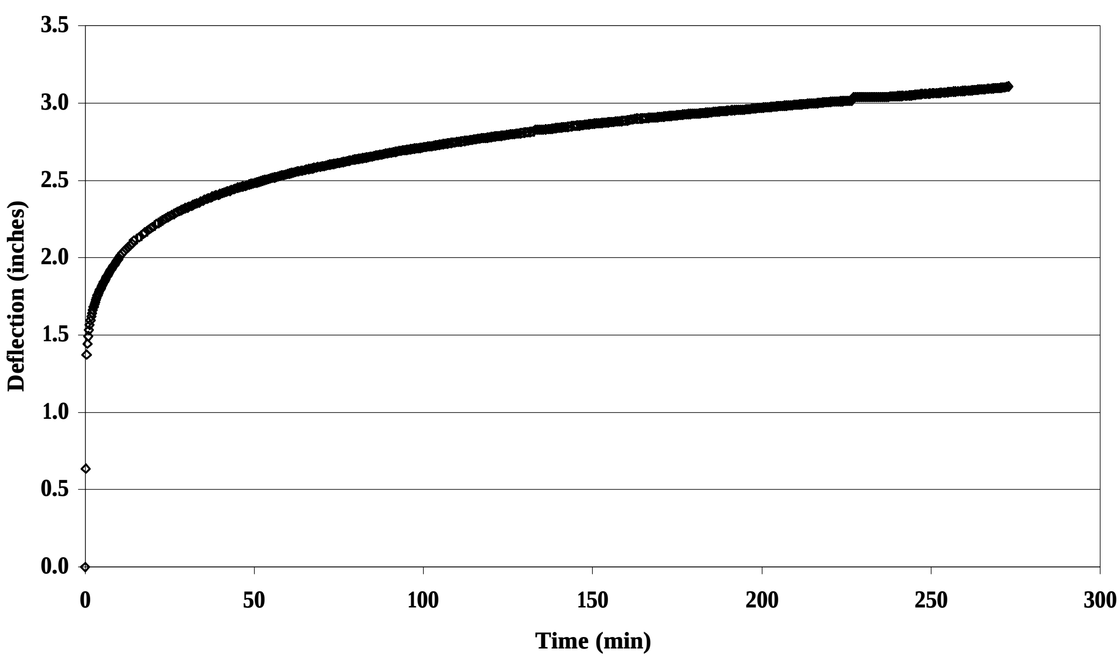

Deflection vs. Time at 73.2% of Ultimate
HDPE w/ MAPE Specimen # 54
Deflection (inches)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
12
14
16
18
20
Time (min)

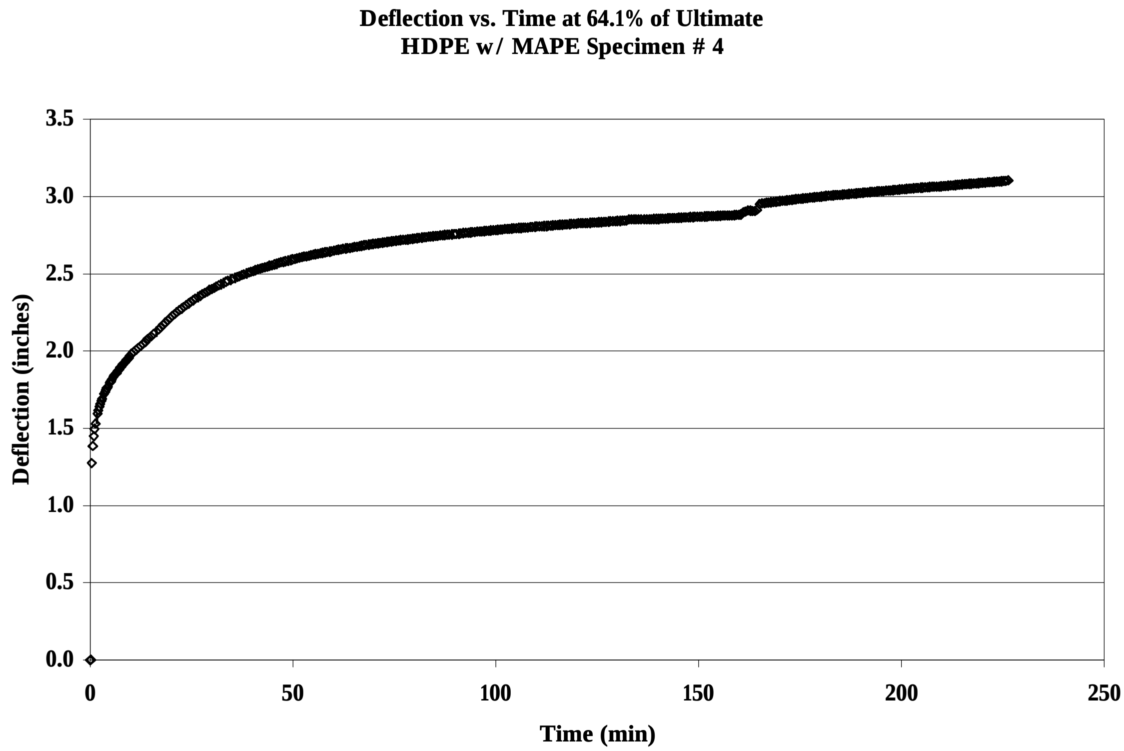

Deflection vs. Time at 64.1% of Ultimate
HDPE w/ MAPE Specimen # 44
Deflection (inches)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
300
350
400
450
500
Time (min)

Deflection vs. Time at 64.1% of Ultimate
HDPE w/ MAPE Specimen # 31

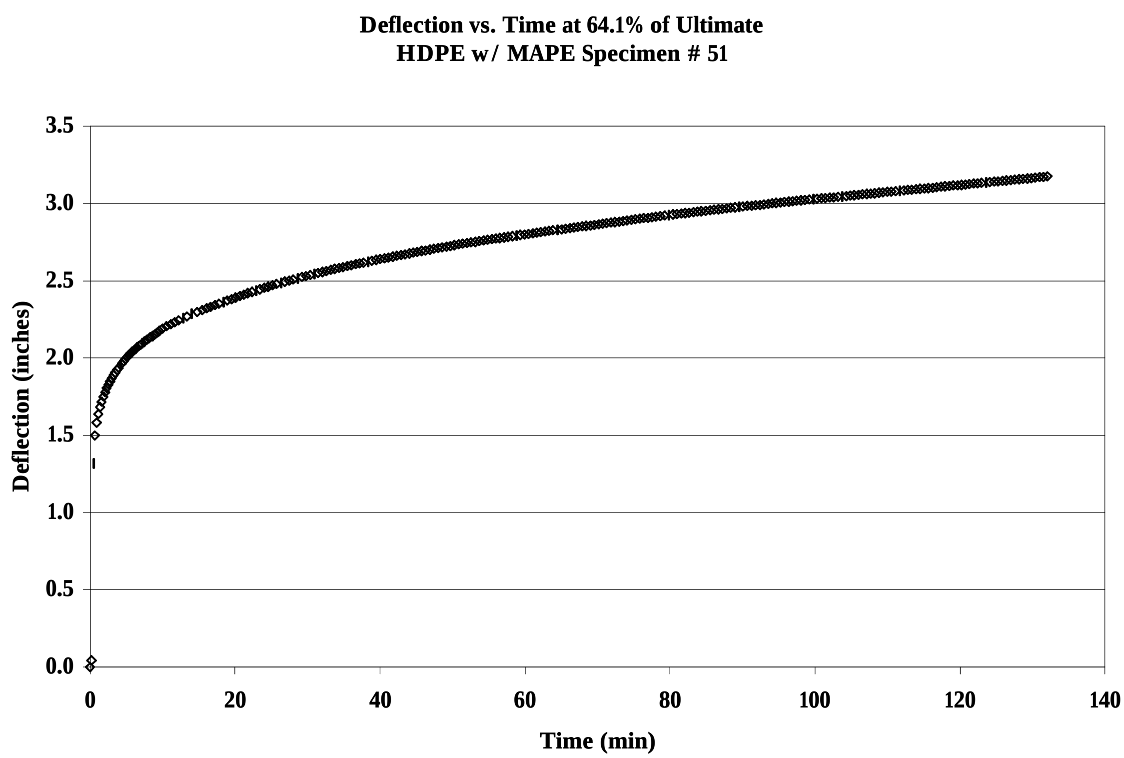


Deflection vs. Time at 64.1% of Ultimate
HDPE w/ MAPE Specimen # 24

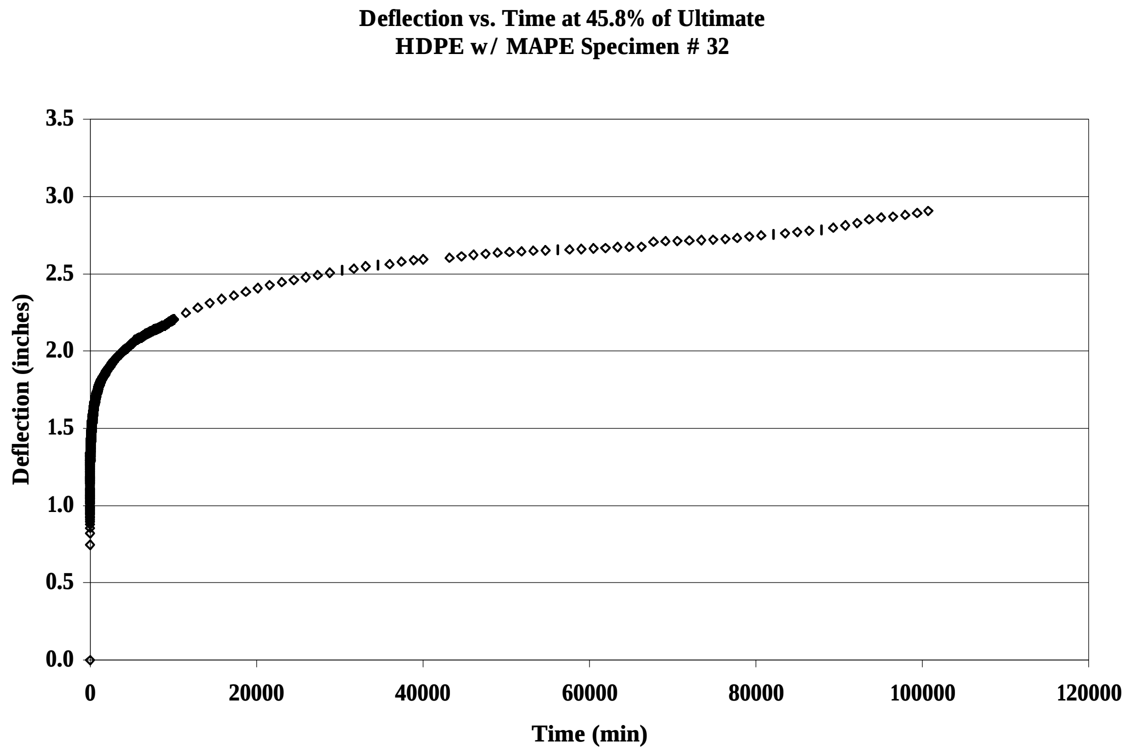


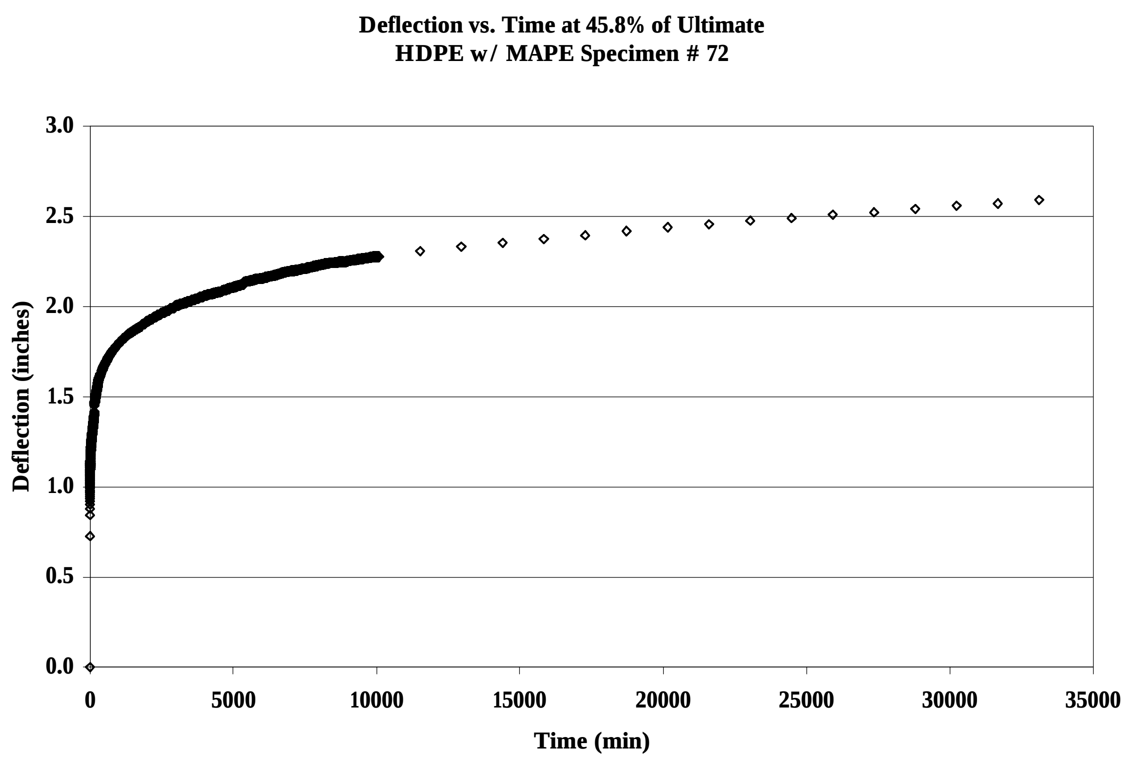


Deflection vs. Time at 64.1% of Ultimate
HDPE w/ MAPE Specimen # 4
Deflection (inches)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
Time (min)

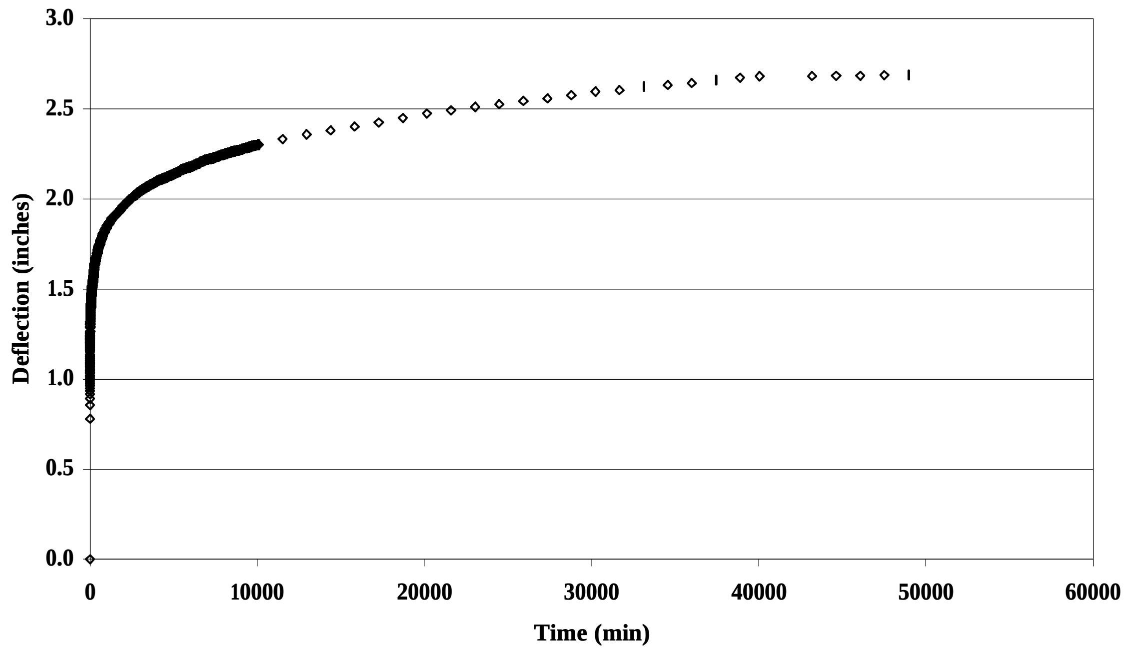


Deflection vs. Time at 64.1% of Ultimate
HDPE w/ MAPE Specimen # 51
Deflection (inches)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
20
40
60
80
100
120
140
Time (min)

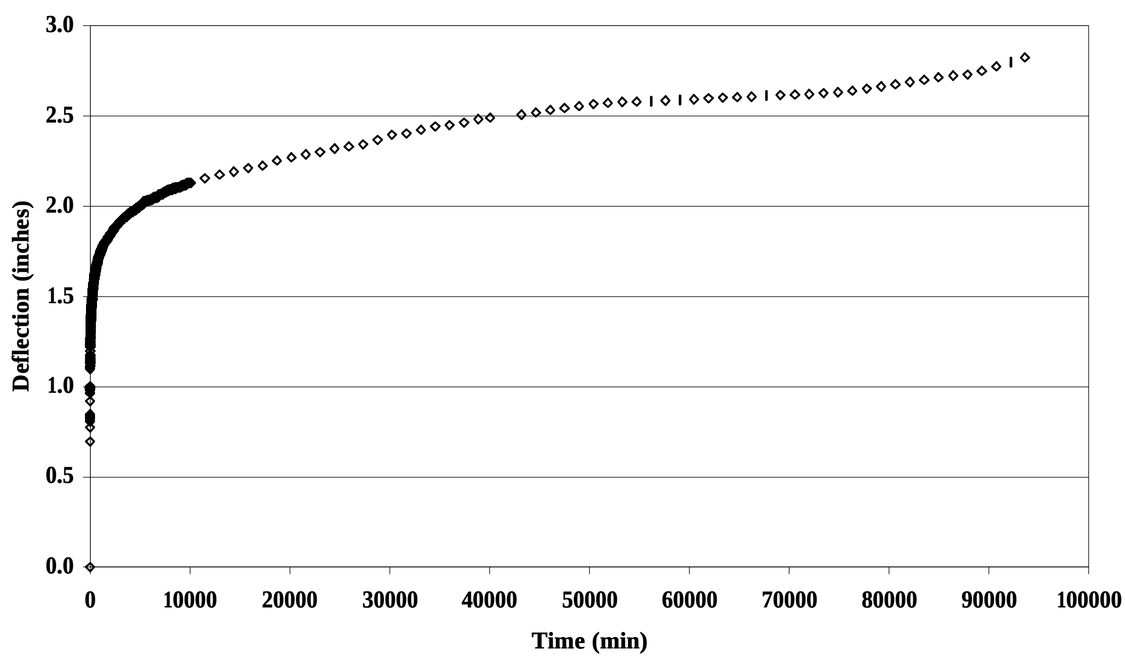

Deflection vs. Time at 45.8% of Ultimate
HDPE w/ MAPE Specimen # 32
Deflection (inches)
Time (min)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
20000
40000
60000
80000
100000
120000

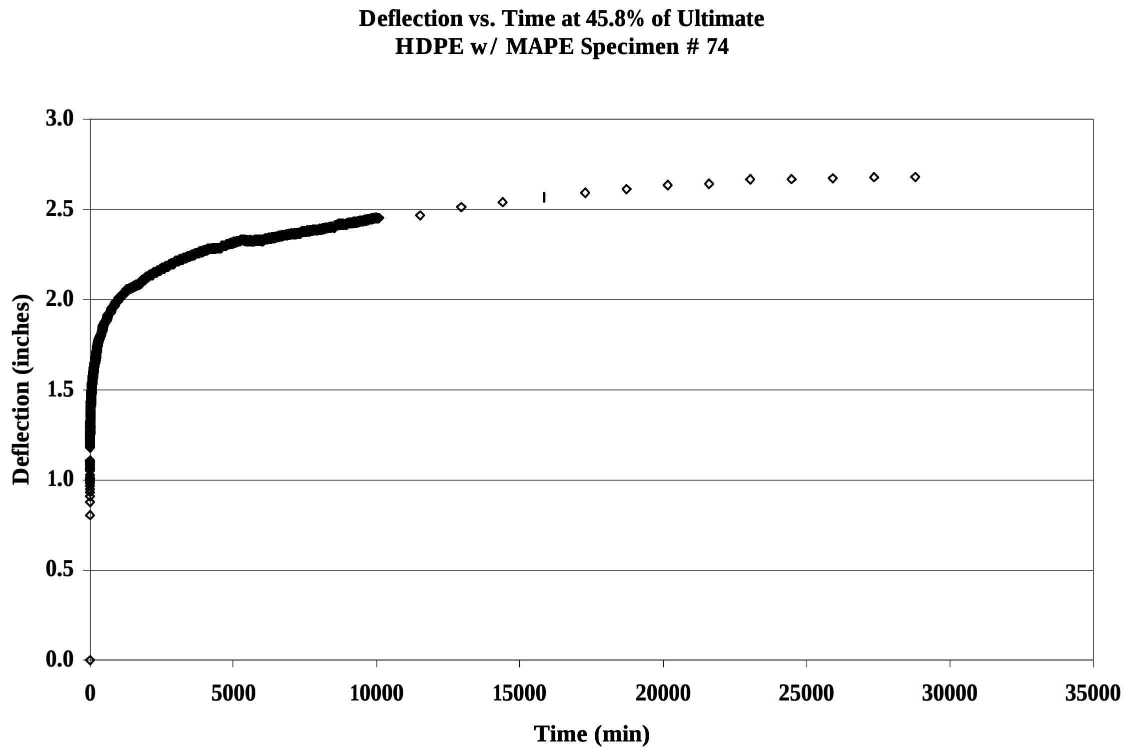

Deflection vs. Time at 45.8% of Ultimate
HDPE w/ MAPE Specimen # 72
Deflection (inches)
Time (min)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
5000
10000
15000
20000
25000
30000
35000

Deflection vs. Time at 45.8% of Ultimate
HDPE w/ MAPE Specimen # 71



Deflection vs. Time at 45.8% of Ultimate
HDPE w/ MAPE Specimen # 12





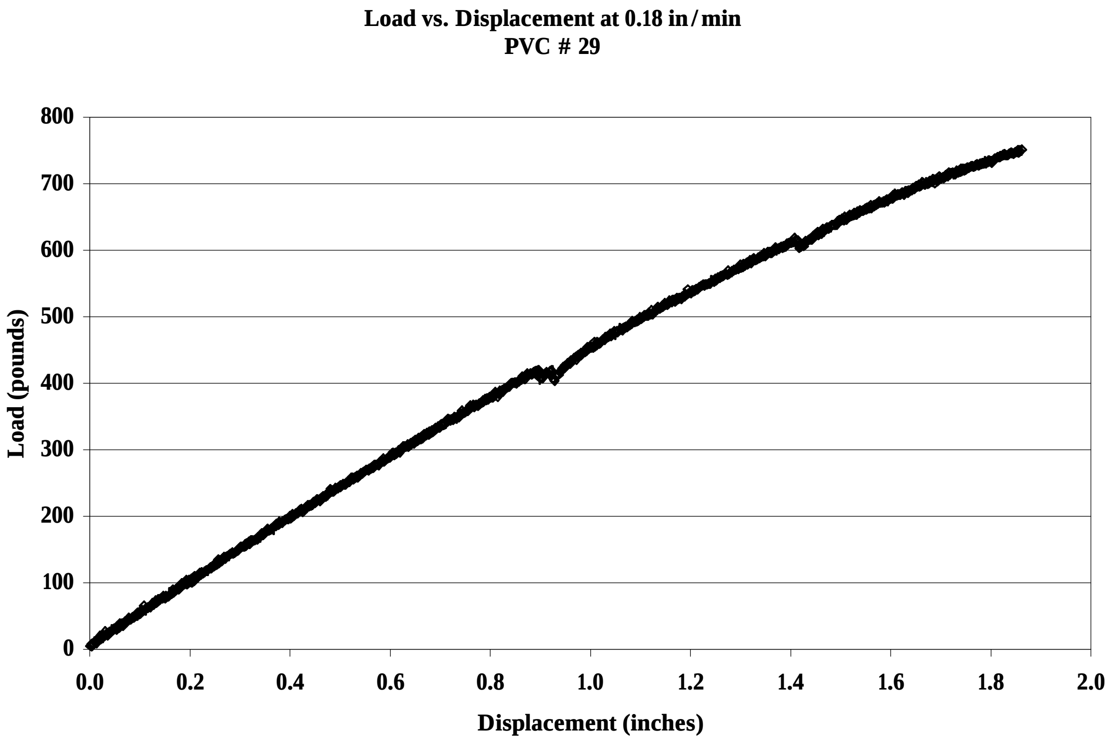
Deflection vs. Time at 45.8% of Ultimate
HDPE w/ MAPE Specimen # 74
Deflection (inches)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
5000
10000
15000
20000
25000
30000
35000
Time (min)

APPENDIX C

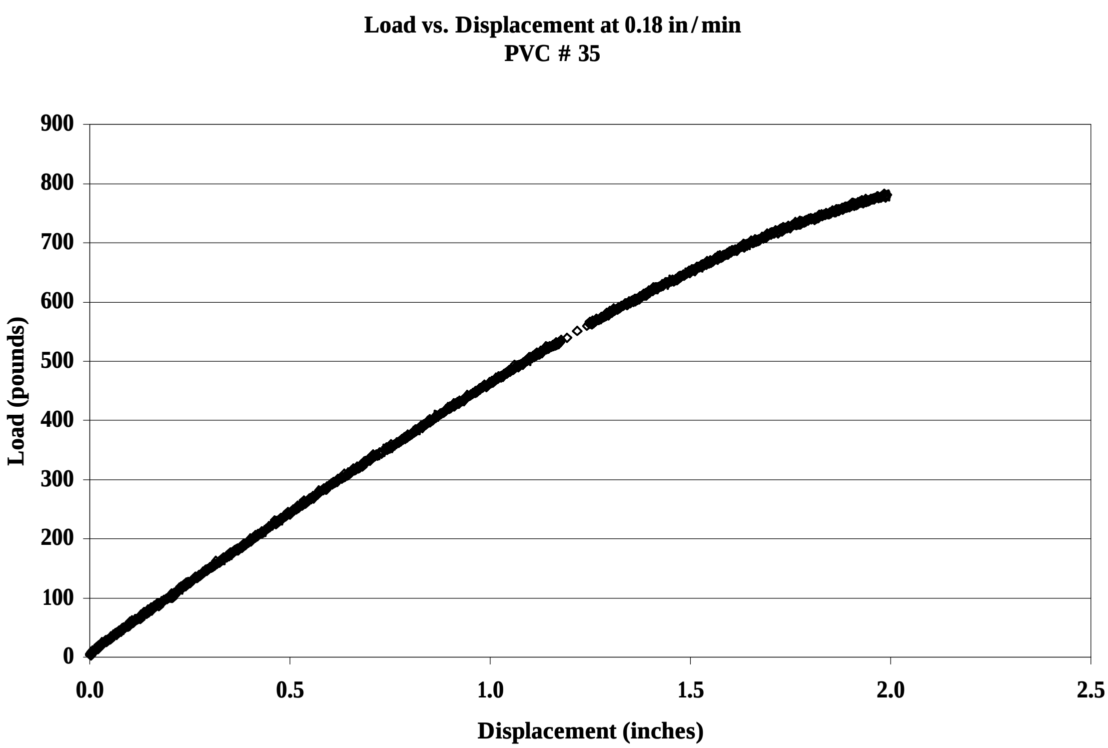
LOAD VS. DISPLACEMENT PLOTS

INTRODUCTION

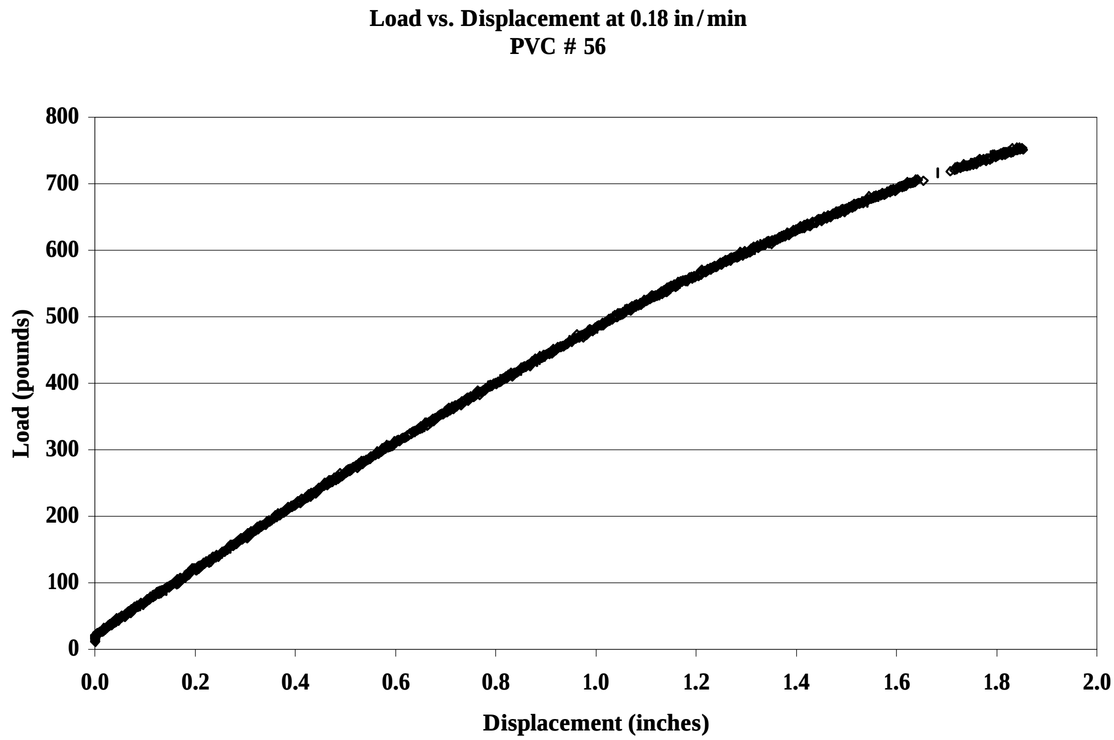
Load versus displacement plots were created for each specimen tested as part of the rate-of-load effect investigation. These plots can be found on the following pages and are arranged by formulation in the following order: PVC, HDPE 8, HDPE 67.5, and HDPE 67.5 w/ MAPE. Within each formulation, the plots are in ascending order of applied load rate. In many of the plots, a small jump in load is observed at a relatively low load. This is not a characteristic of the material, but is due to an uncontrollable slip of the test apparatus hardware.

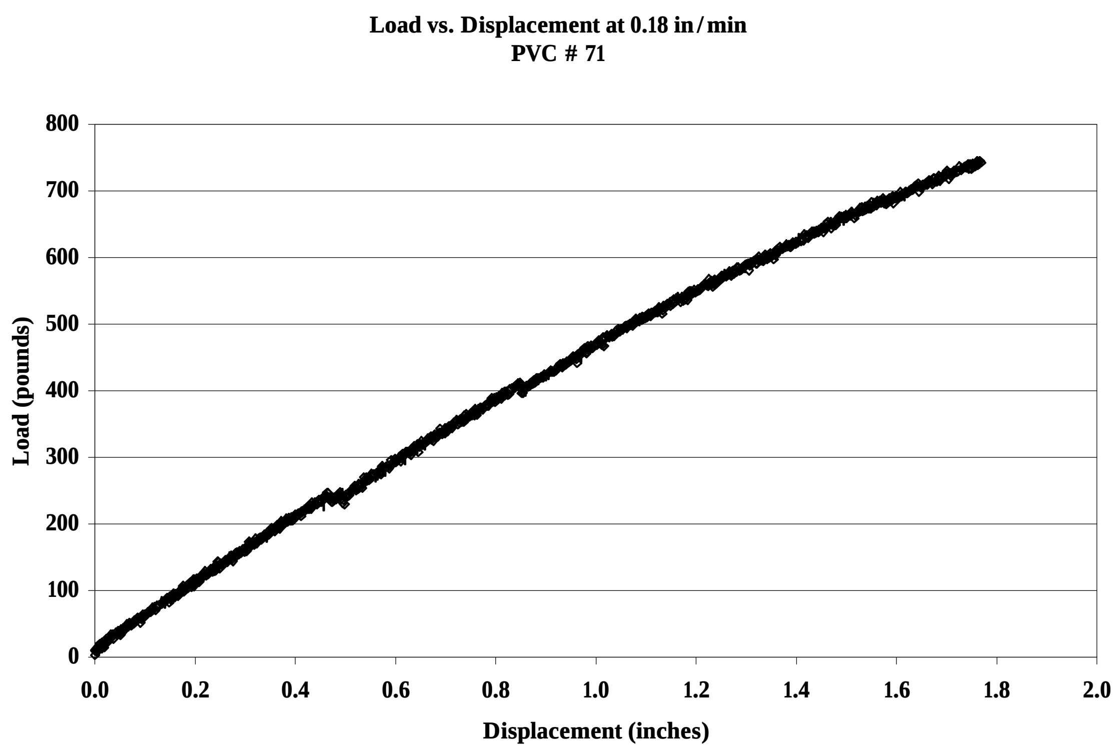


Load vs. Displacement at 0.18 in/min
PVC # 29
Load (pounds)
0
100
200
300
400
500
600
700
800
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Displacement (inches)

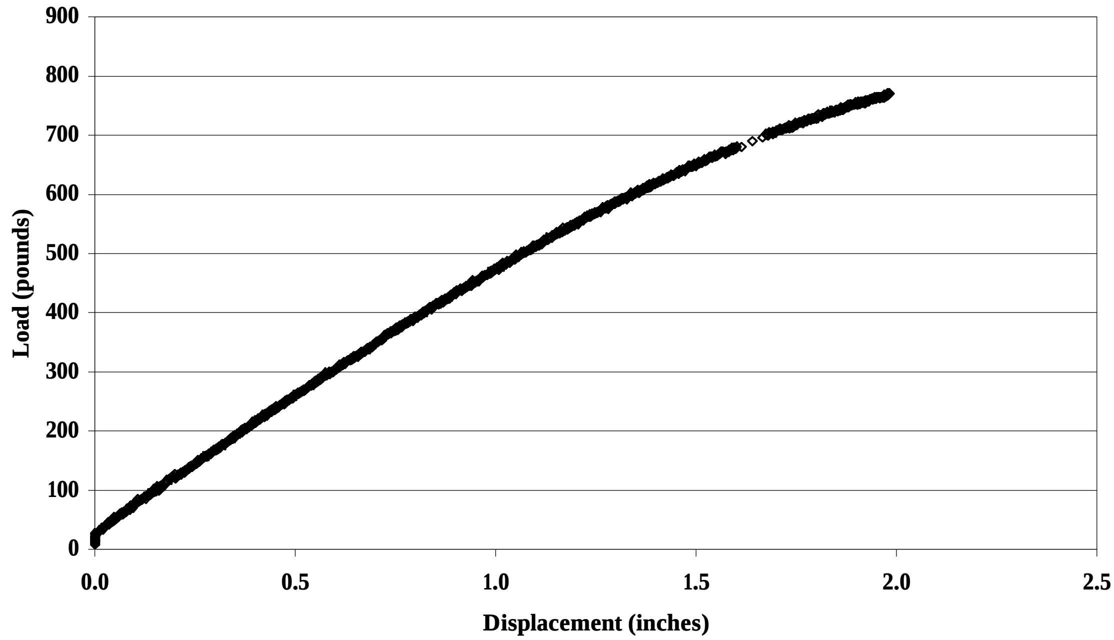


Load vs. Displacement at 0.18 in/min
PVC # 35
Load (pounds)
0
100
200
300
400
500
600
700
800
900
0.0
0.5
1.0
1.5
2.0
2.5
Displacement (inches)

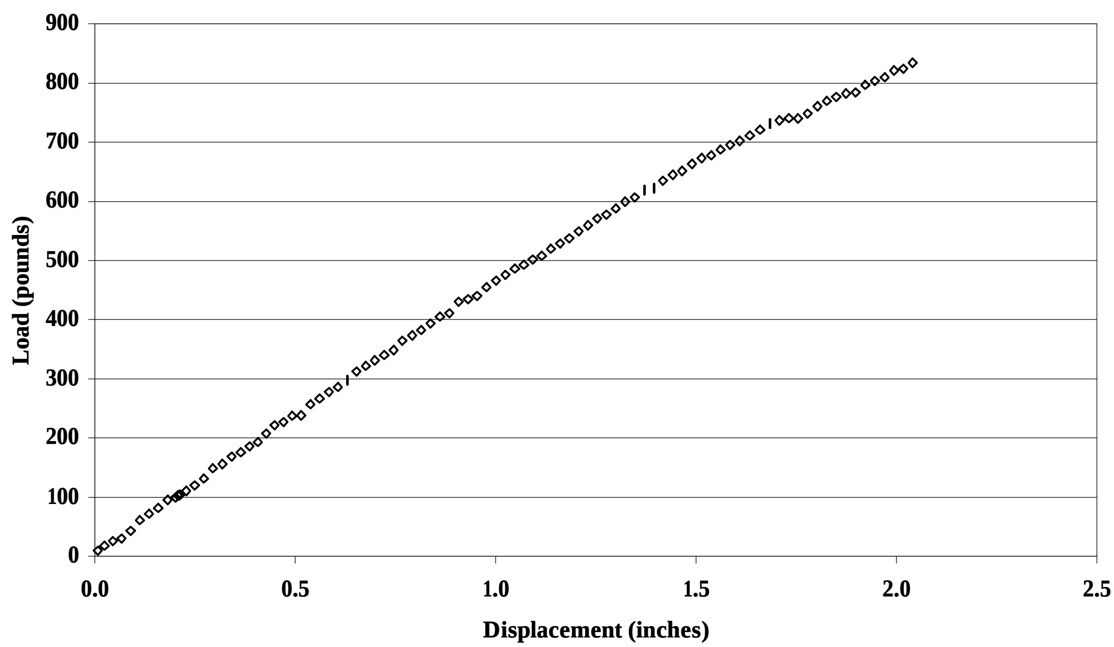

Load vs. Displacement at 0.18 in/min
PVC # 56
Load (pounds)
800
700
600
500
400
300
200
100
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Displacement (inches)

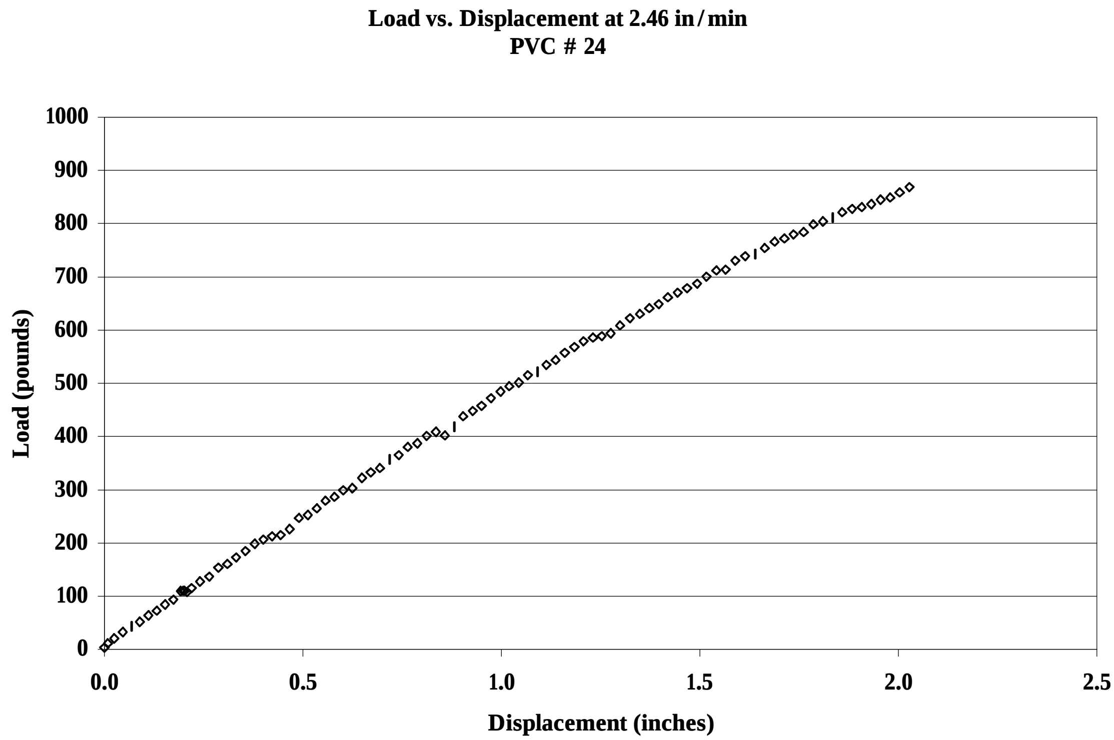

Load vs. Displacement at 0.18 in/min
PVC # 71
Load (pounds)
800
700
600
500
400
300
200
100
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Displacement (inches)

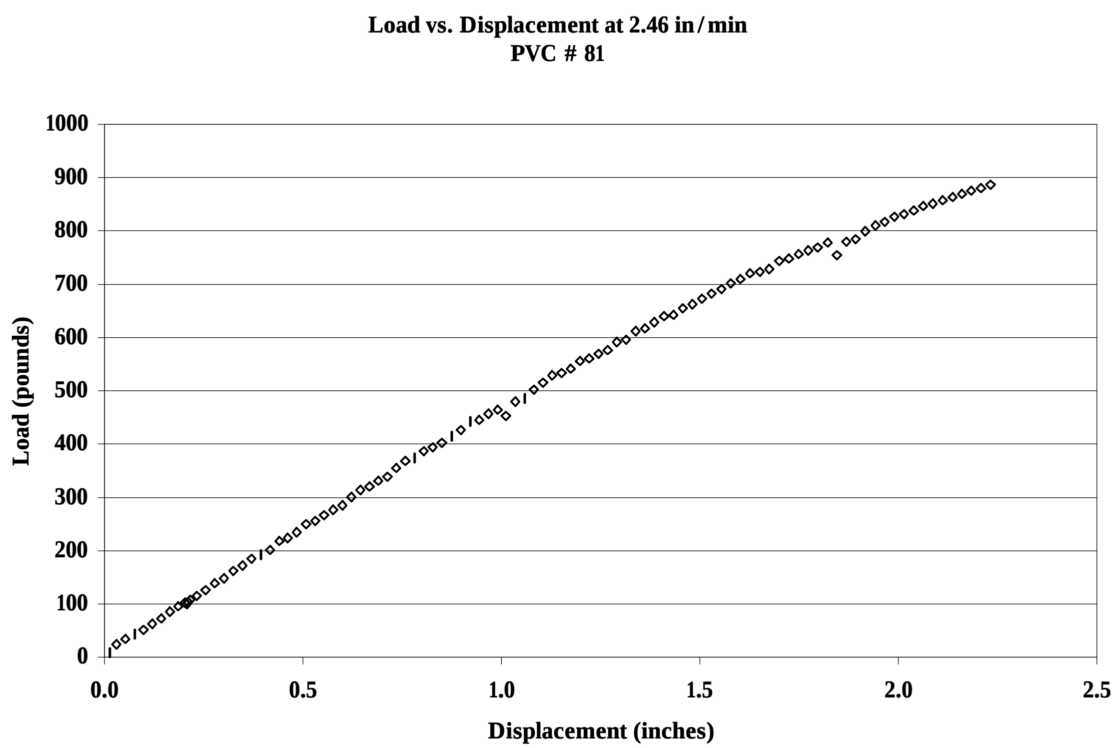
Load vs. Displacement at 0.18 in / min
PVC # 72

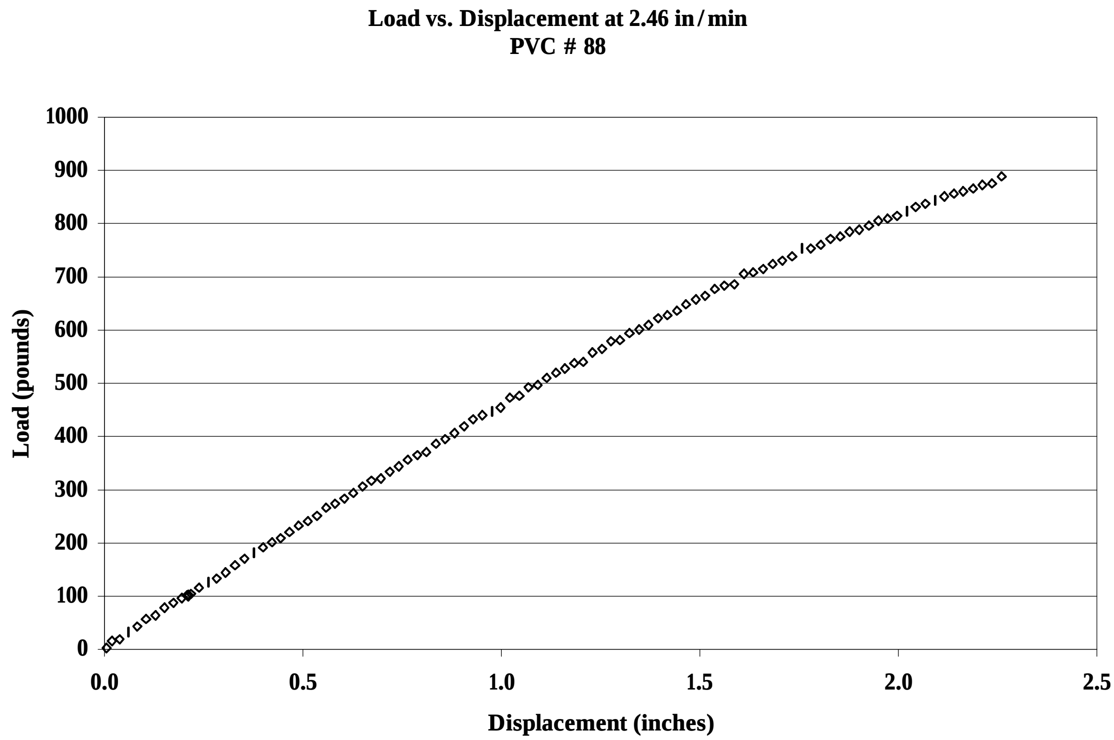


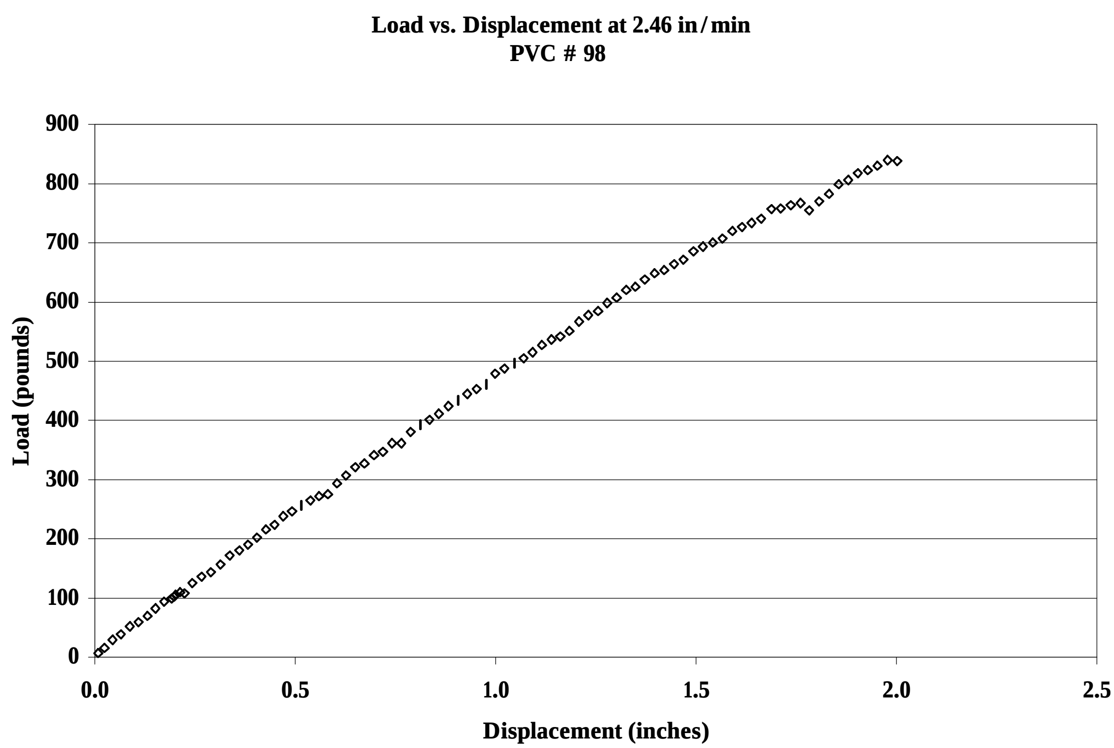
Load vs. Displacement at 2.46 in / min
PVC # 23

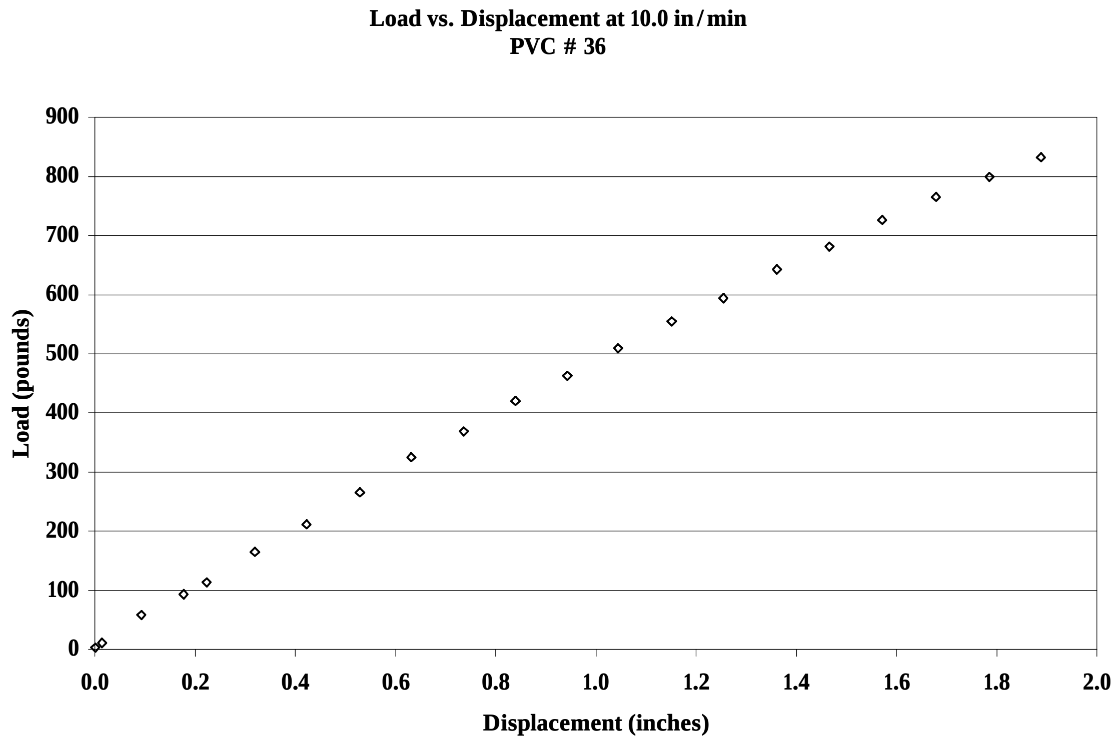


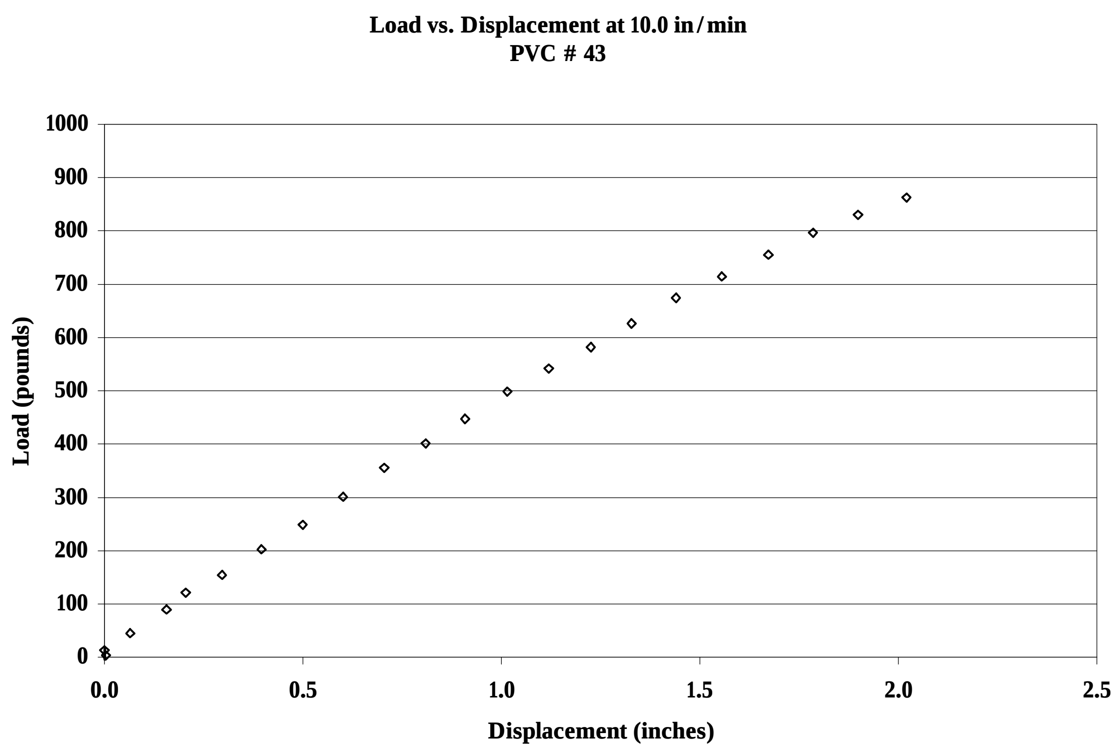

Load vs. Displacement at 2.46 in/min
PVC # 24
Load (pounds)
0
100
200
300
400
500
600
700
800
900
1000
0.0
0.5
1.0
1.5
2.0
2.5
Displacement (inches)


Load vs. Displacement at 2.46 in/min
PVC # 81
Load (pounds)
0
100
200
300
400
500
600
700
800
900
1000
0.0
0.5
1.0
1.5
2.0
2.5
Displacement (inches)

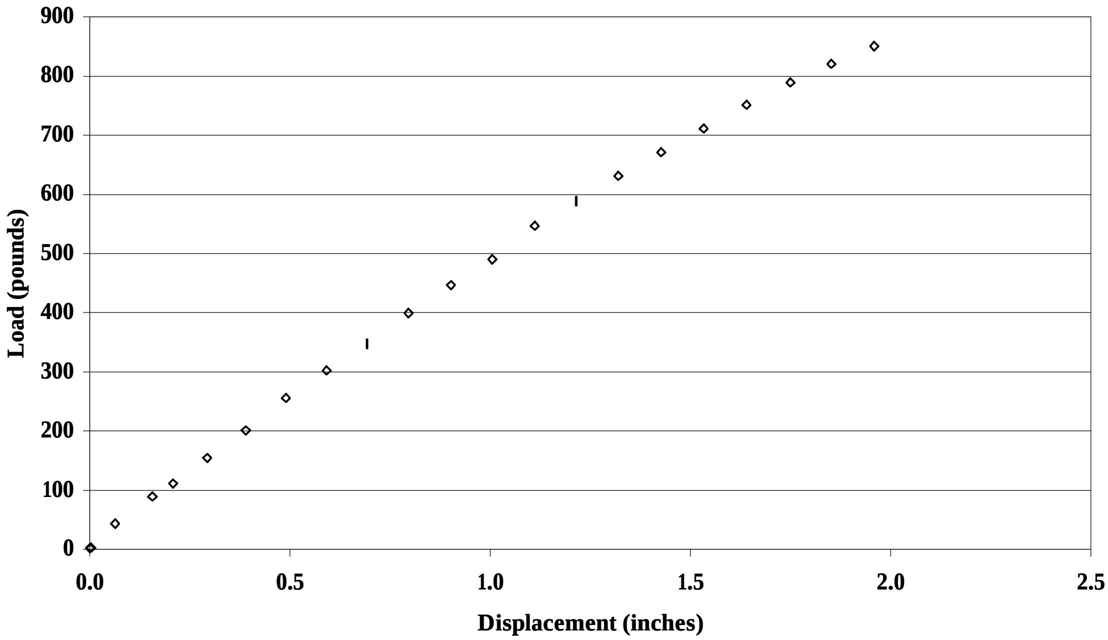

Load vs. Displacement at 2.46 in/min
PVC # 88
Load (pounds)
Displacement (inches)
0
100
200
300
400
500
600
700
800
900
1000
0.0
0.5
1.0
1.5
2.0
2.5


Load vs. Displacement at 2.46 in/min
PVC # 98
Load (pounds)
Displacement (inches)
0
100
200
300
400
500
600
700
800
900
0.0
0.5
1.0
1.5
2.0
2.5

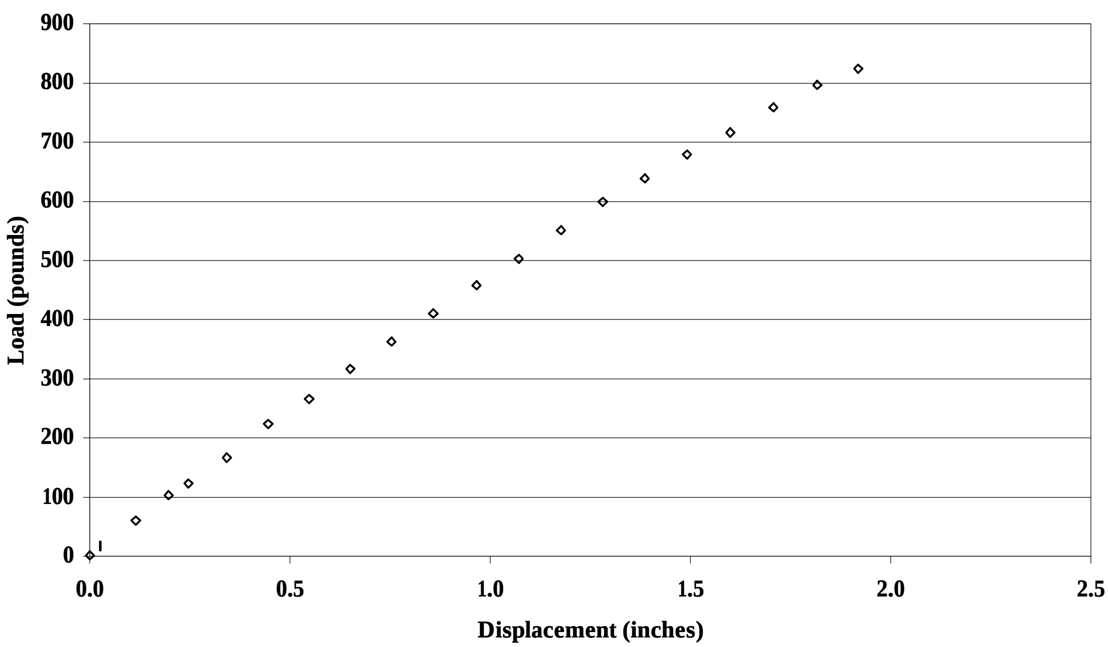

Load vs. Displacement at 10.0 in/min
PVC # 36
Load (pounds)
0
100
200
300
400
500
600
700
800
900
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Displacement (inches)

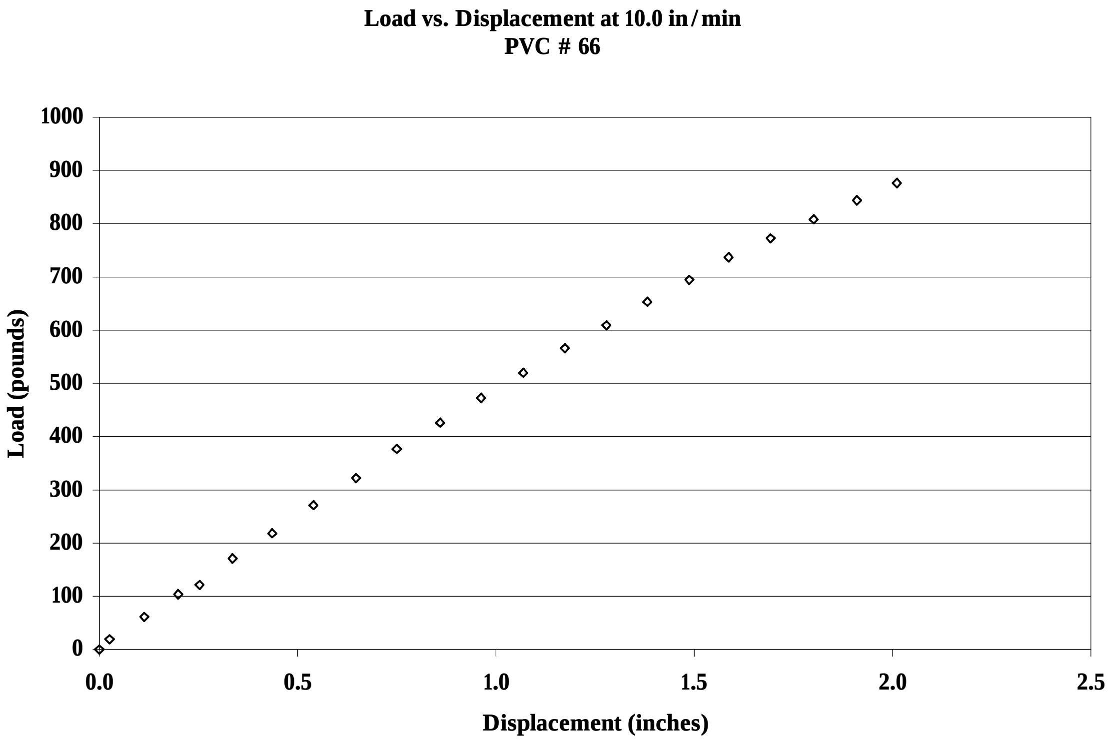

Load vs. Displacement at 10.0 in/min
PVC # 43
Load (pounds)
0
100
200
300
400
500
600
700
800
900
1000
0.0
0.5
1.0
1.5
2.0
2.5
Displacement (inches)

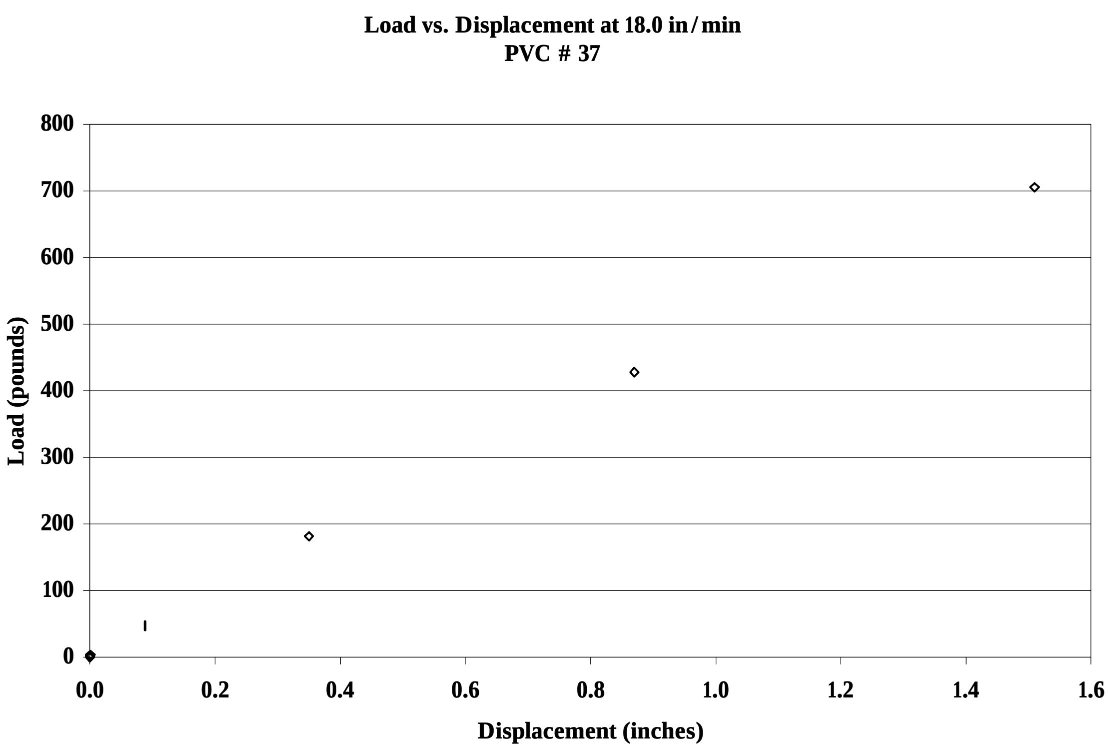
Load vs. Displacement at 10.0 in/min
PVC # 47



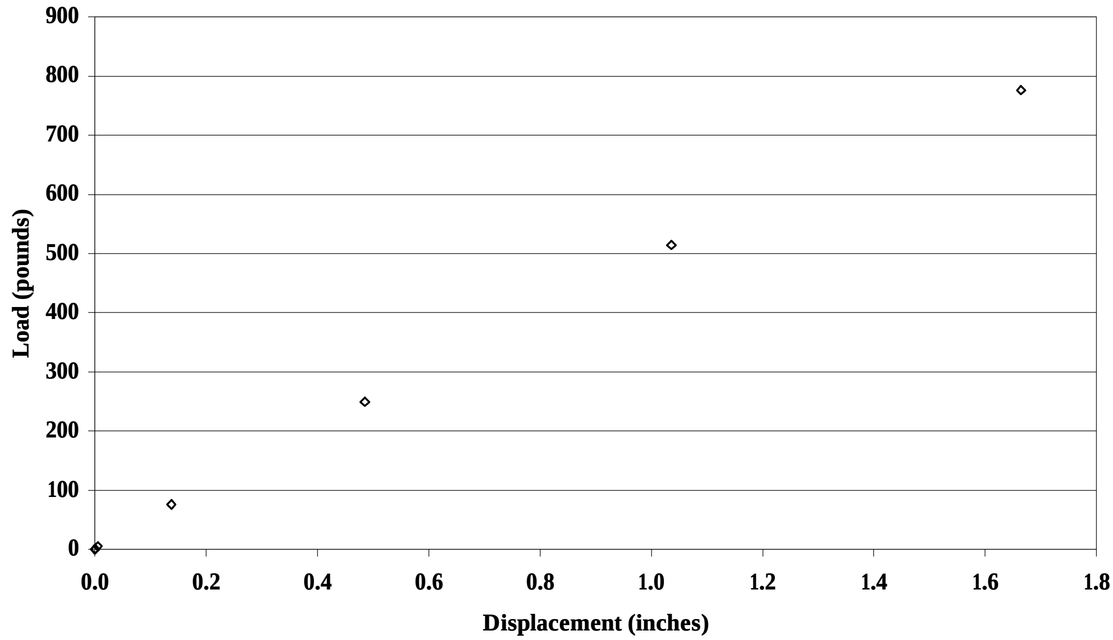
Load vs. Displacement at 10.0 in/min
PVC # 55



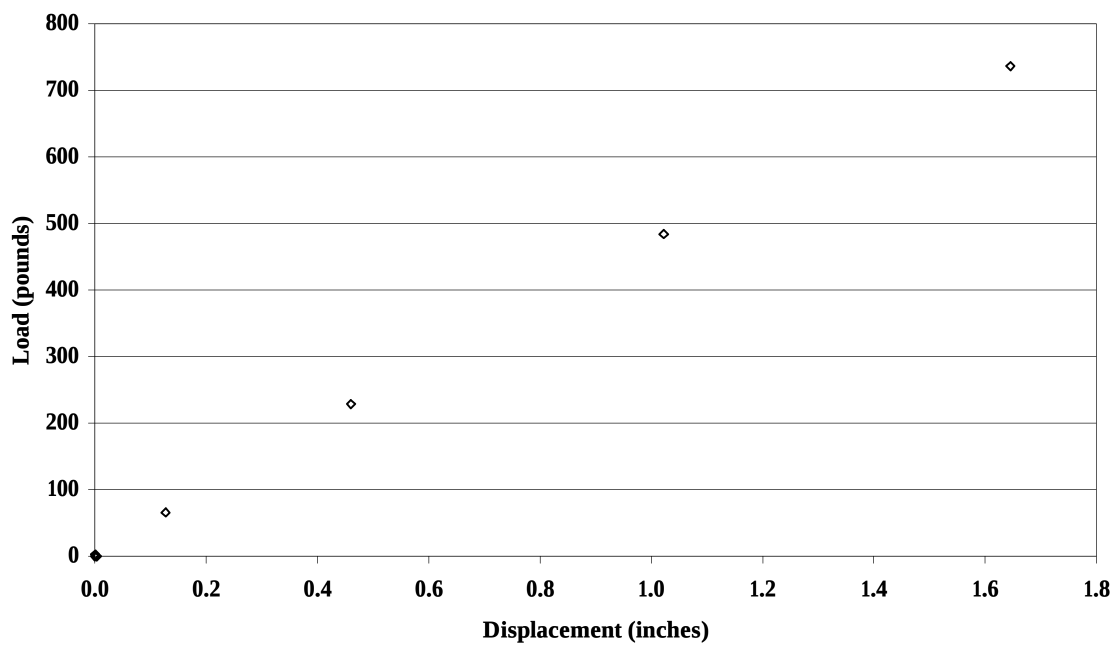

Load vs. Displacement at 10.0 in/min
PVC # 66
Load (pounds)
1000
900
800
700
600
500
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
Displacement (inches)

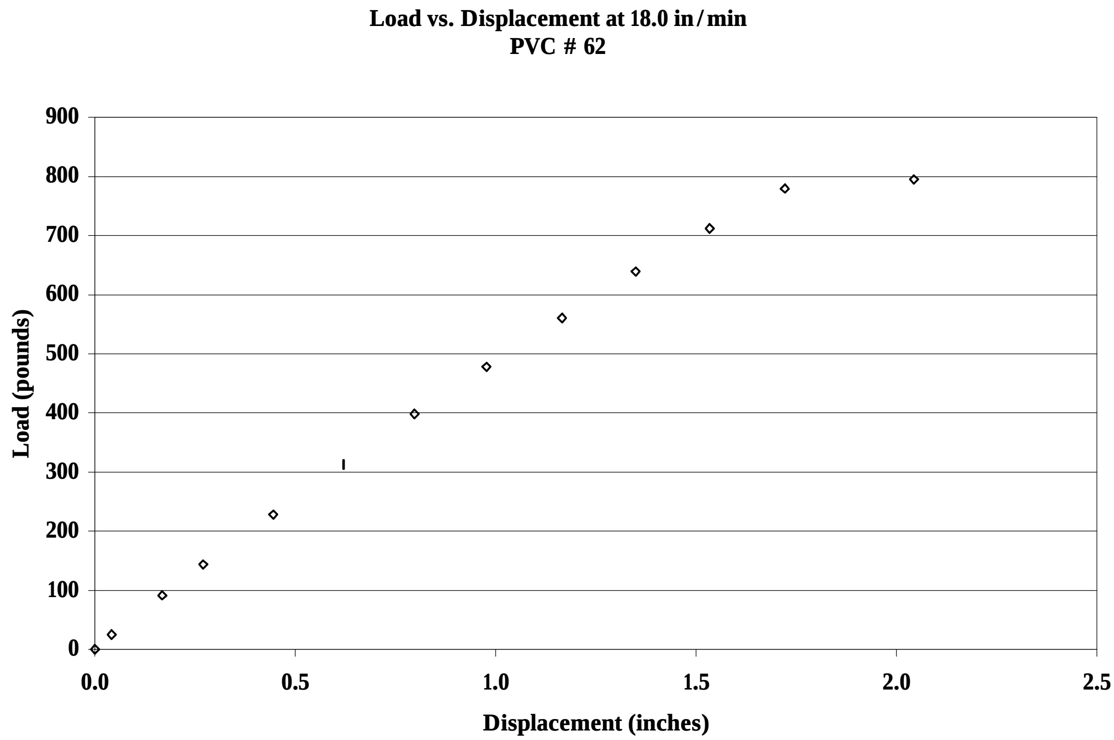

Load vs. Displacement at 18.0 in/min
PVC # 37
Load (pounds)
800
700
600
500
400
300
200
100
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Displacement (inches)

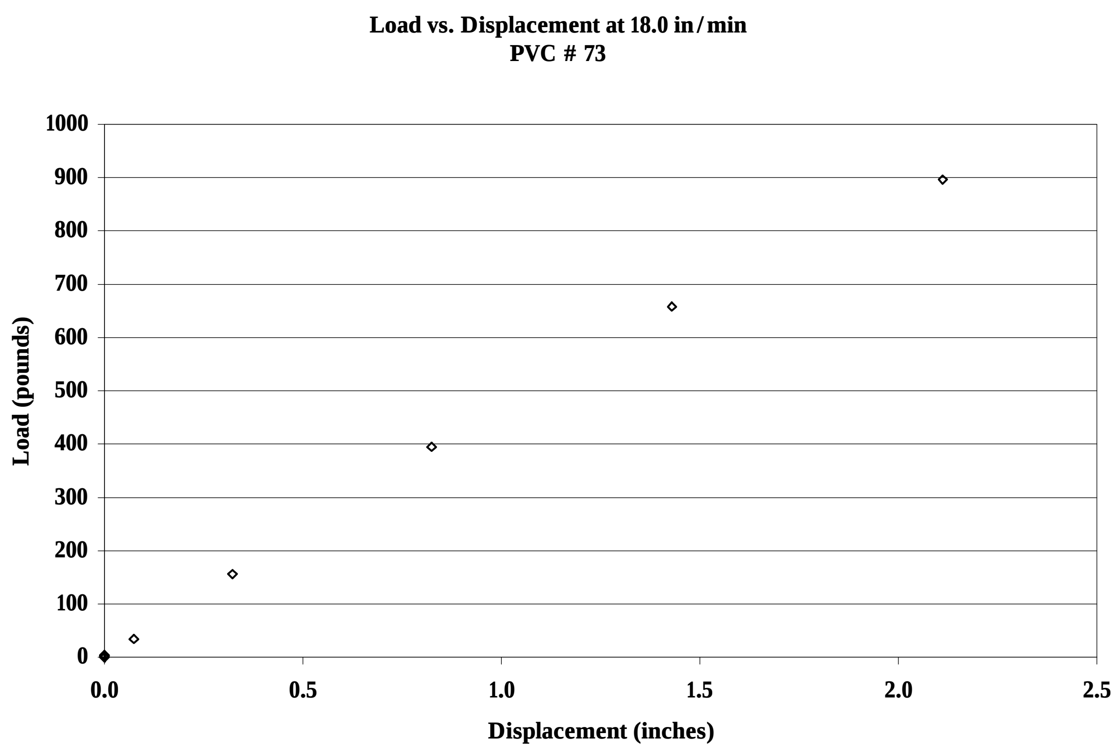
Load vs. Displacement at 18.0 in/min
PVC # 39

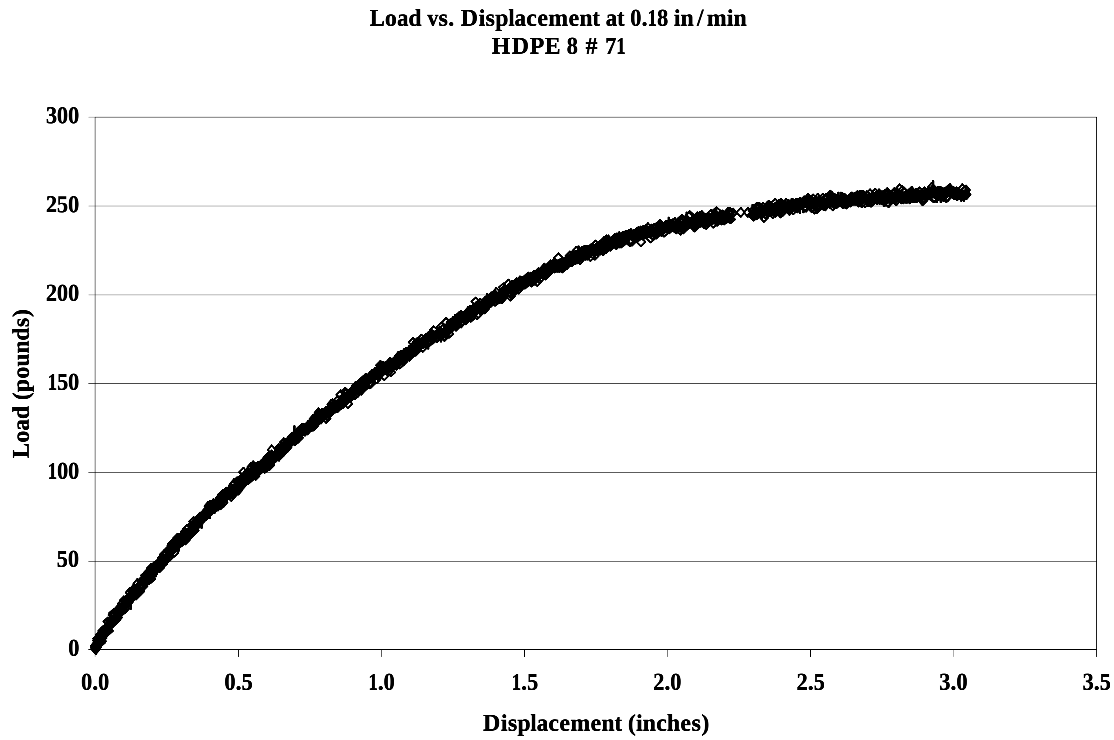


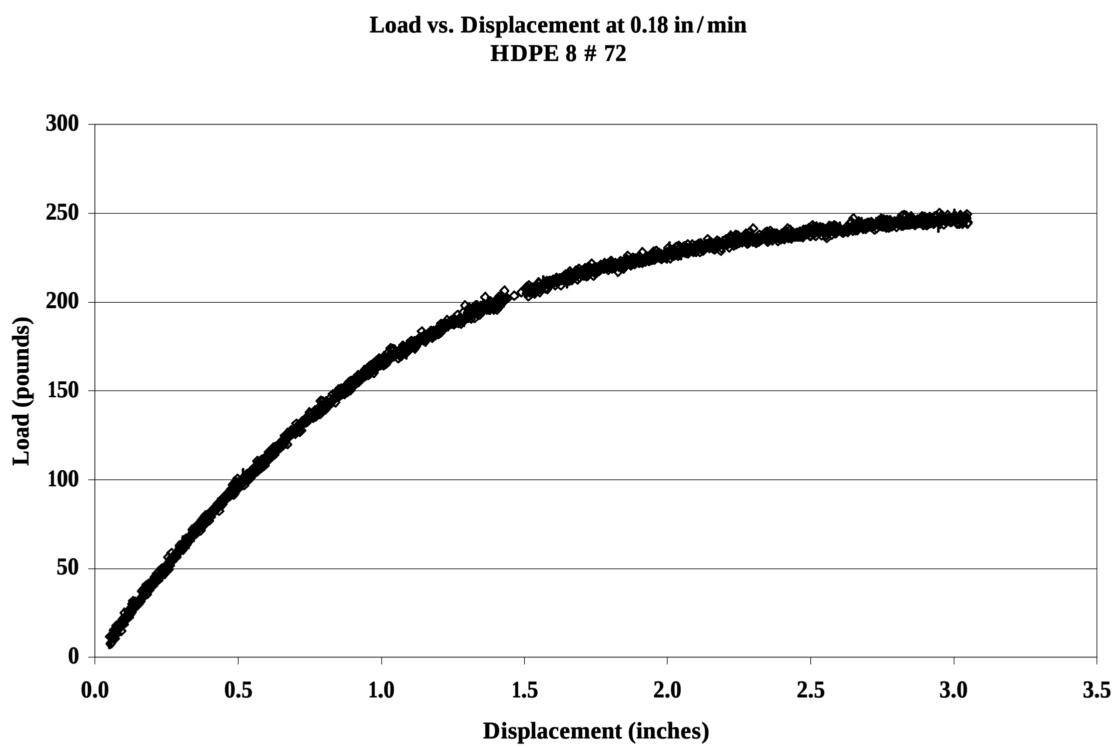
Load vs. Displacement at 18.0 in/min
PVC # 45



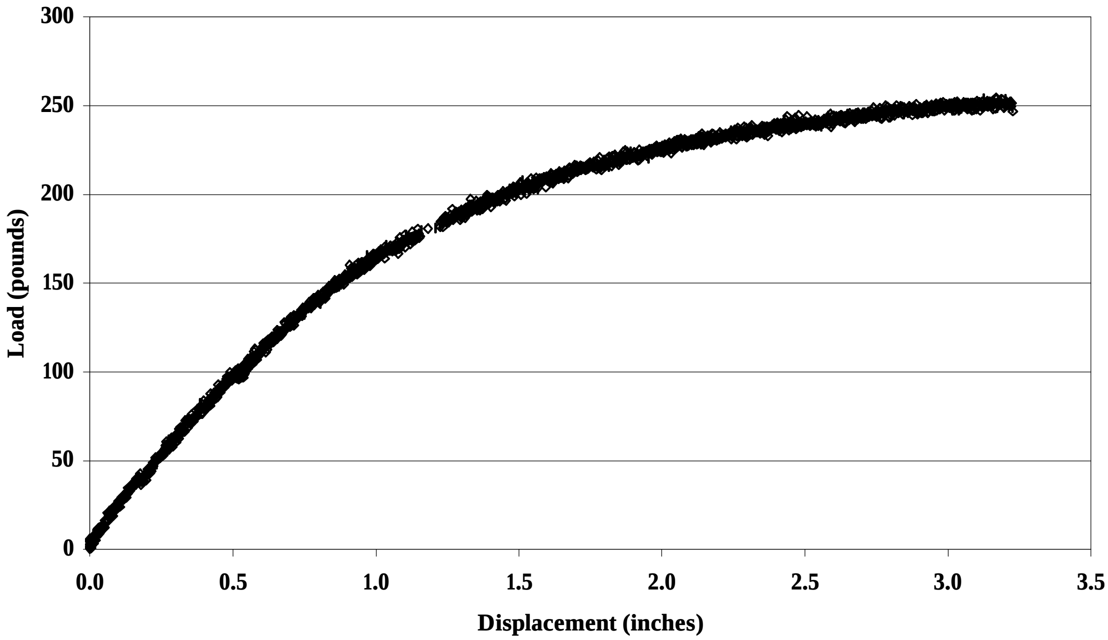

Load vs. Displacement at 18.0 in/min
PVC # 62
Load (pounds)
Displacement (inches)
0
100
200
300
400
500
600
700
800
900
0.0
0.5
1.0
1.5
2.0
2.5


Load vs. Displacement at 18.0 in/min
PVC # 73
Load (pounds)
Displacement (inches)
0
100
200
300
400
500
600
700
800
900
1000
0.0
0.5
1.0
1.5
2.0
2.5

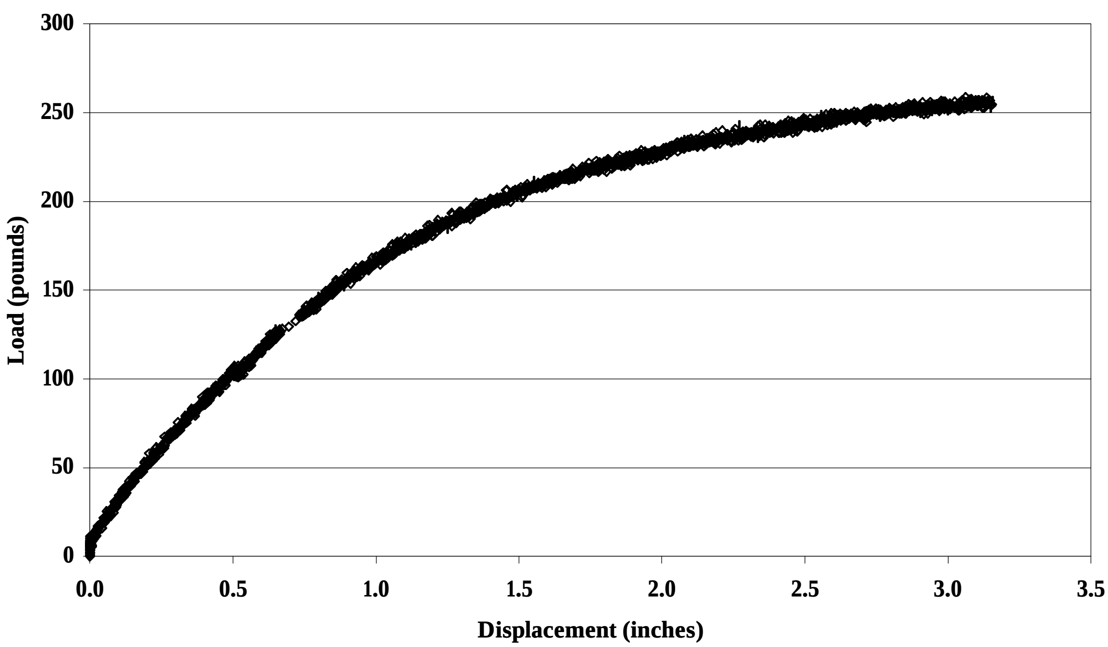

Load vs. Displacement at 0.18 in/min
HDPE 8 # 71
Load (pounds)
300
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Displacement (inches)


Load vs. Displacement at 0.18 in/min
HDPE 8 # 72
Load (pounds)
300
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Displacement (inches)

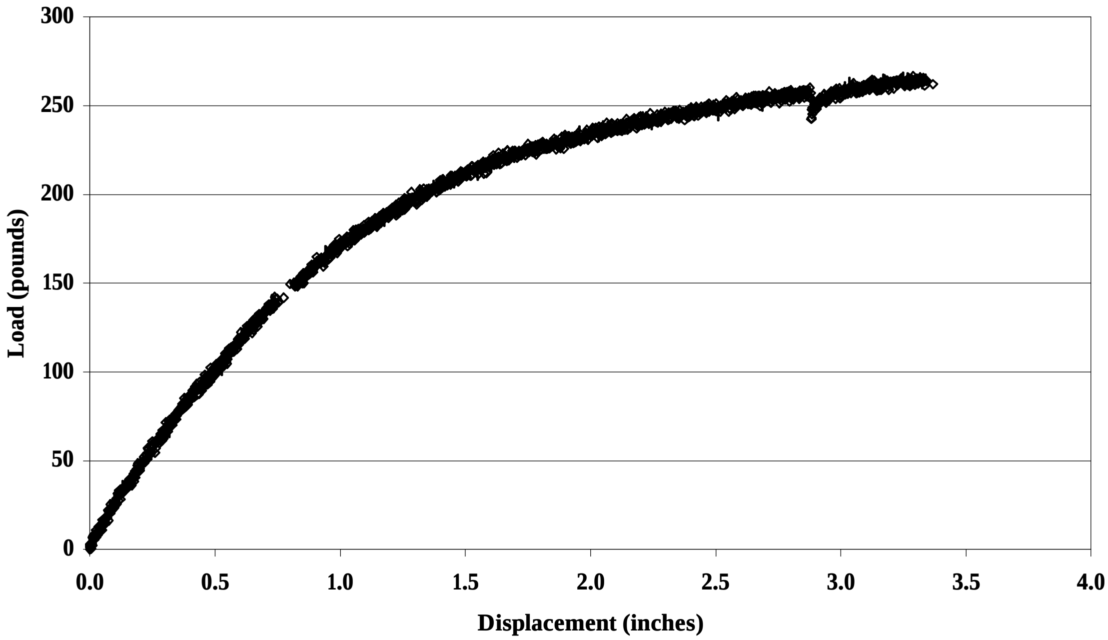
Load vs. Displacement at 0.18 in/min
HDPE 8 # 77



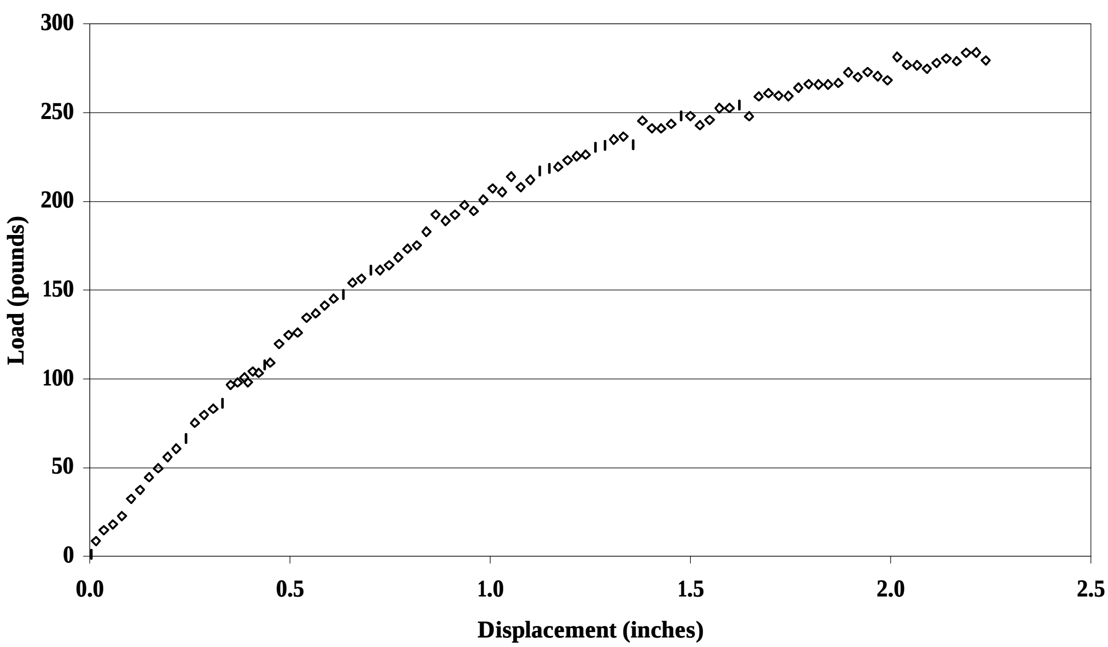
Load vs. Displacement at 0.18 in/min
HDPE 8 # 89



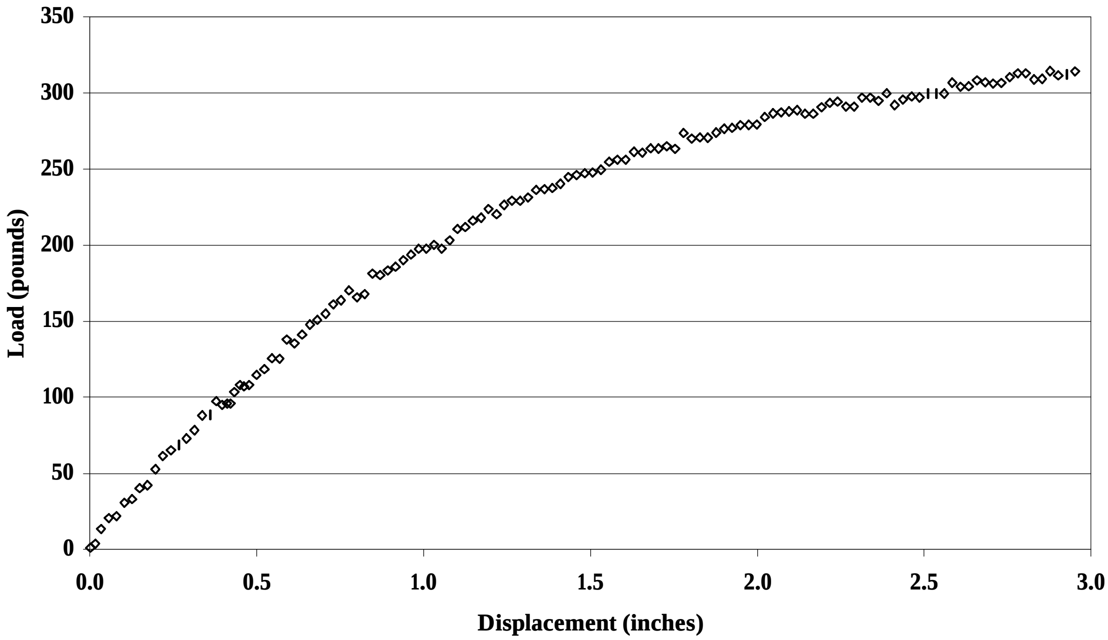
Load vs. Displacement at 0.18 in/min
HDPE 8 # 92



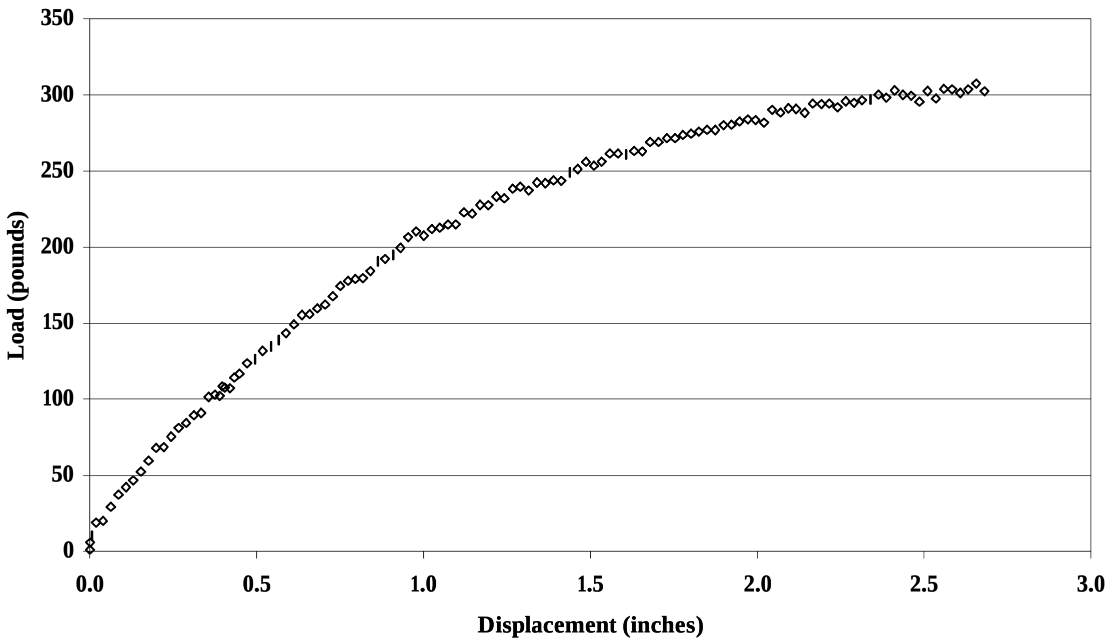
Load vs. Displacement at 2.46 in/min
HDPE 8 # 10



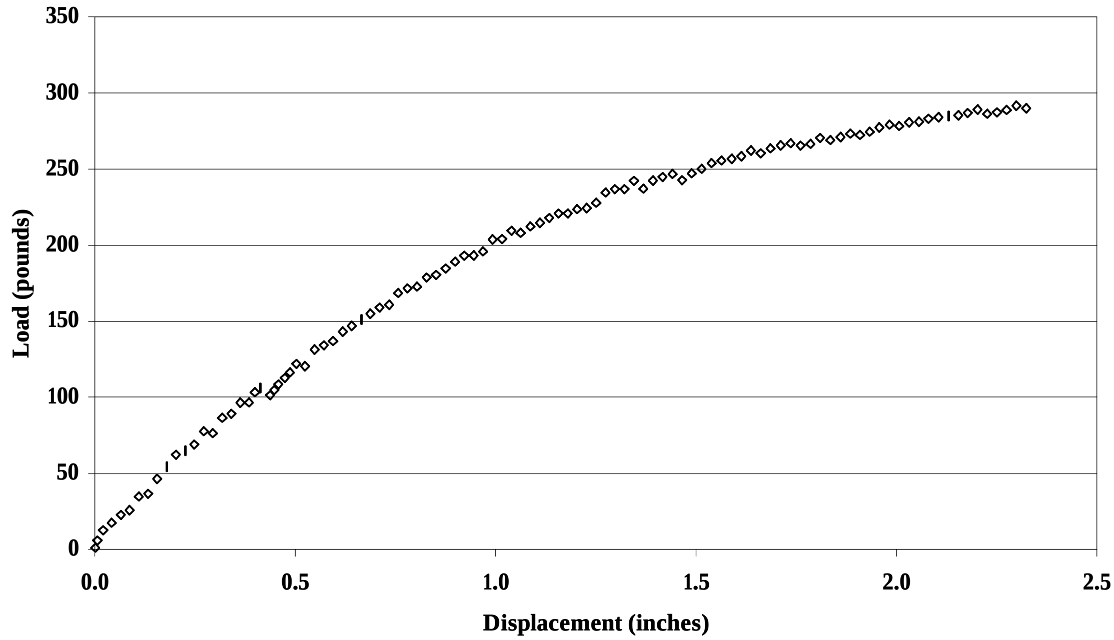
Load vs. Displacement at 2.46 in / min
HDPE 8 # 10



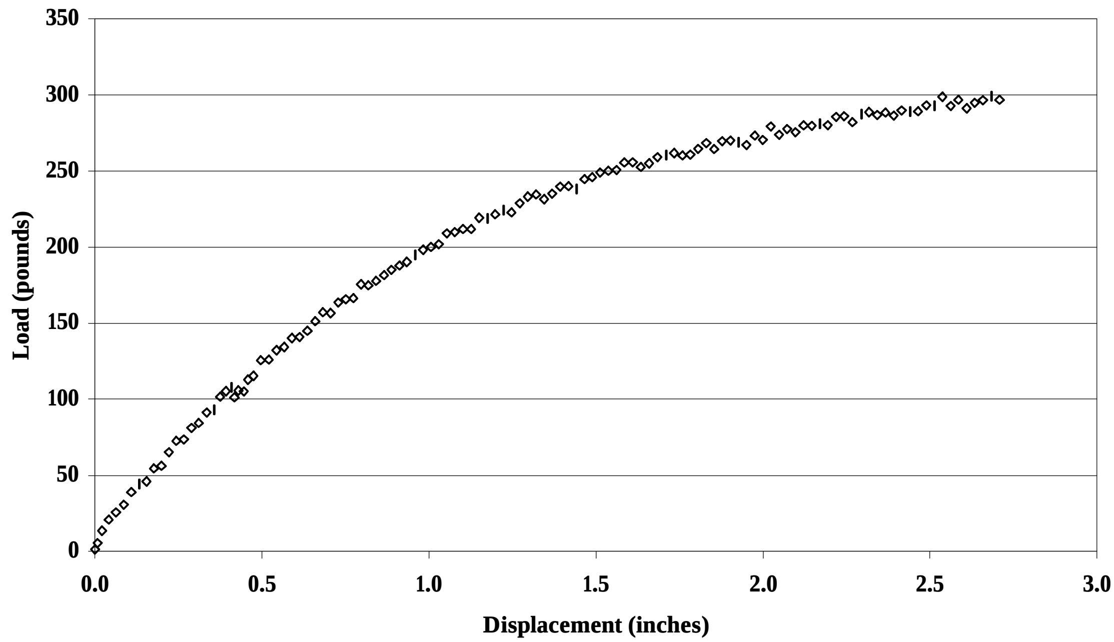
Load vs. Displacement at 2.46 in / min
HDPE 8 # 10



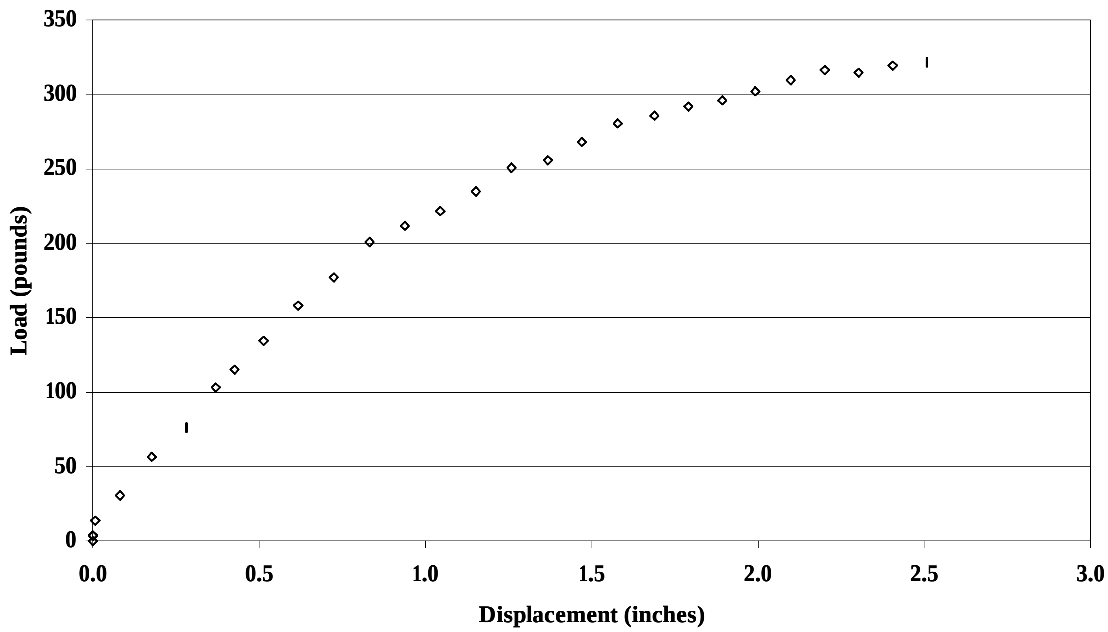
Load vs. Displacement at 2.46 in/min
HDPE 8 # 10



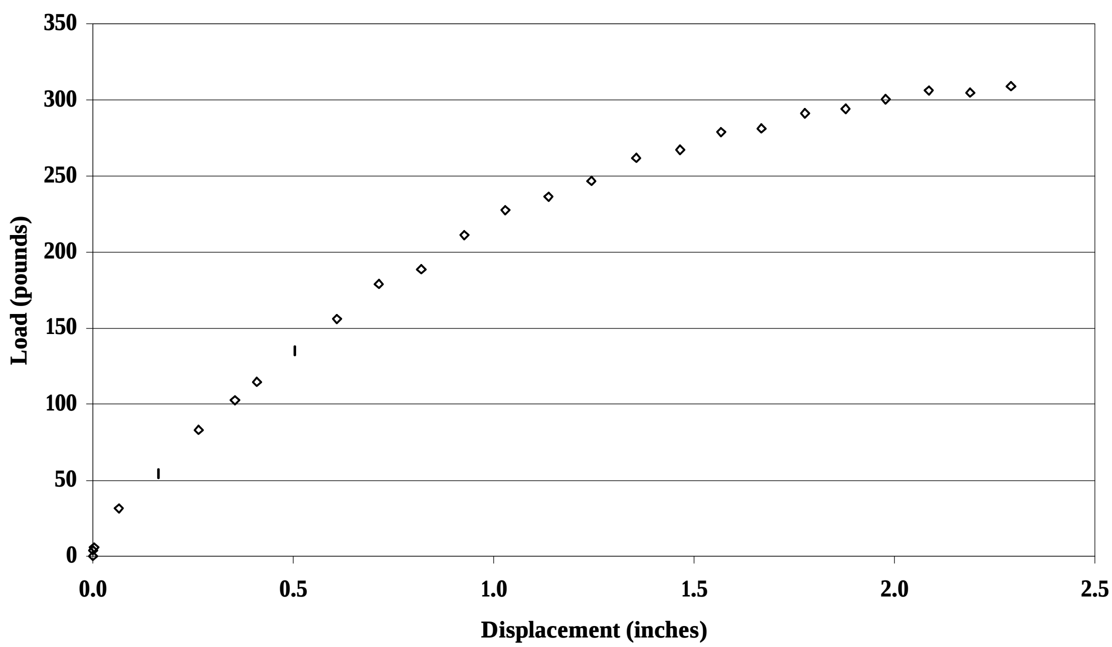
Load vs. Displacement at 2.46 in/min
HDPE 8 # 10



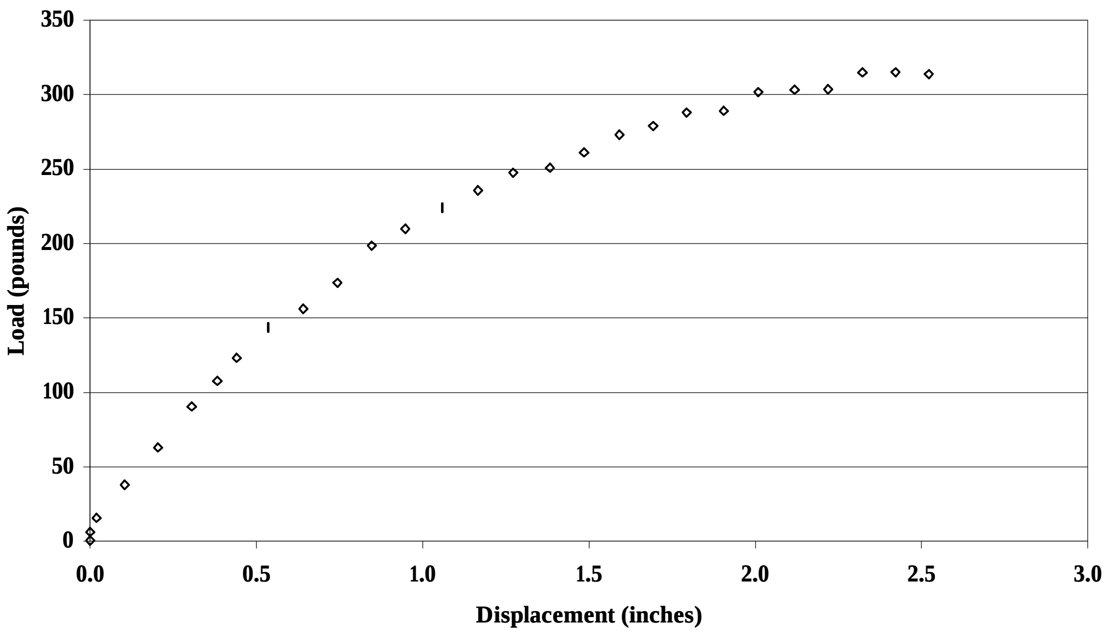
Load vs. Displacement at 10.0 in/min
HDPE 8 # 51



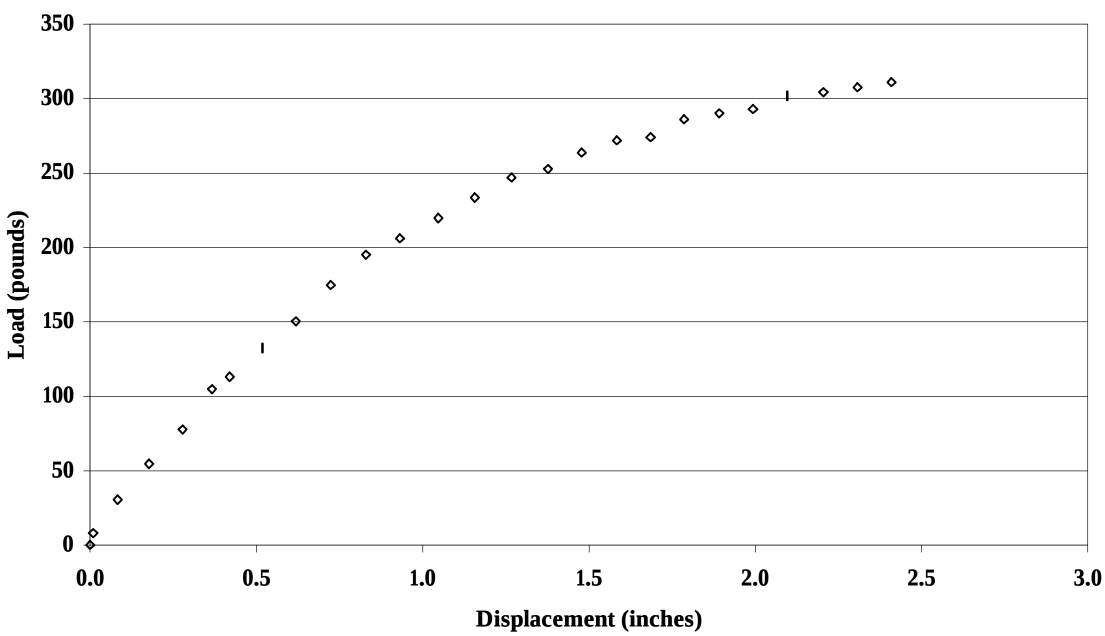
Load vs. Displacement at 10.0 in/min
HDPE 8 # 60



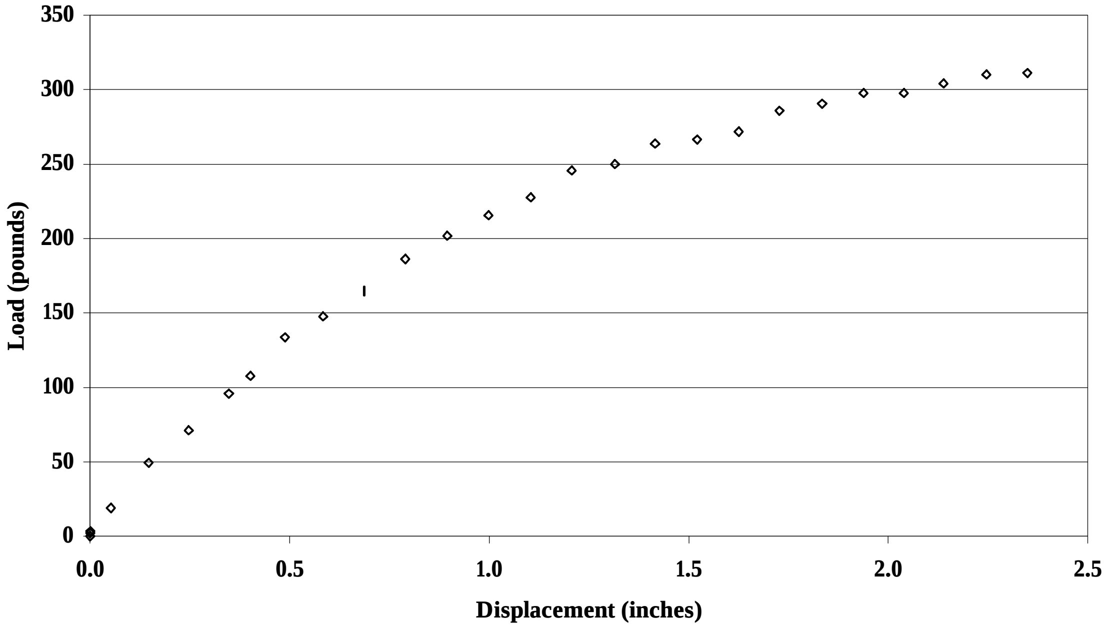
Load vs. Displacement at 10.0 in/min
HDPE 8 # 81



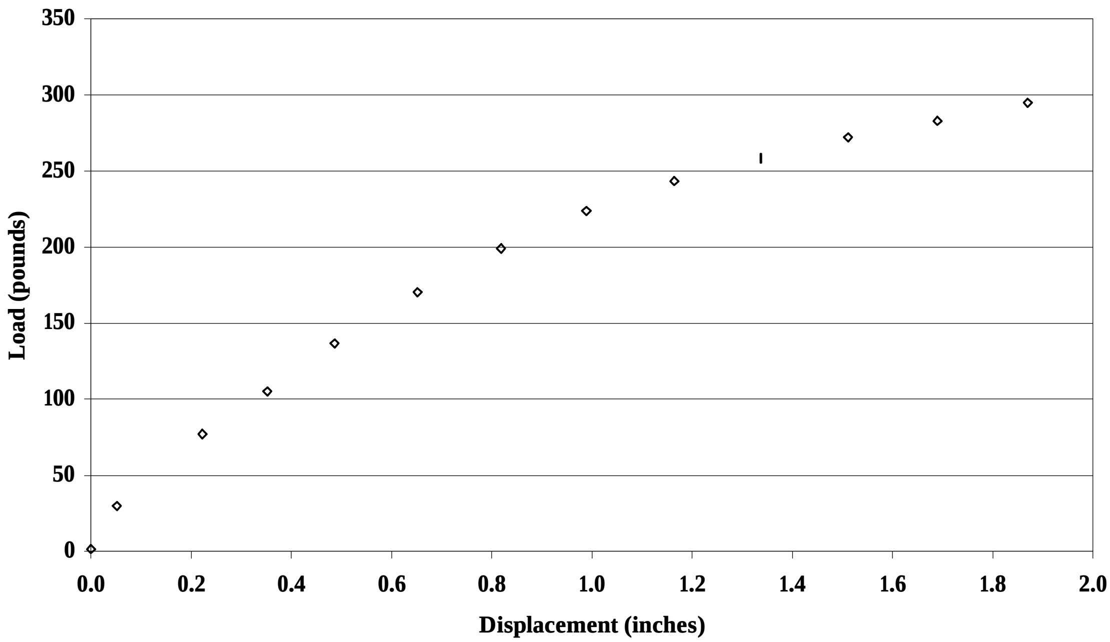
Load vs. Displacement at 10.0 in/min
HDPE 8 # 90

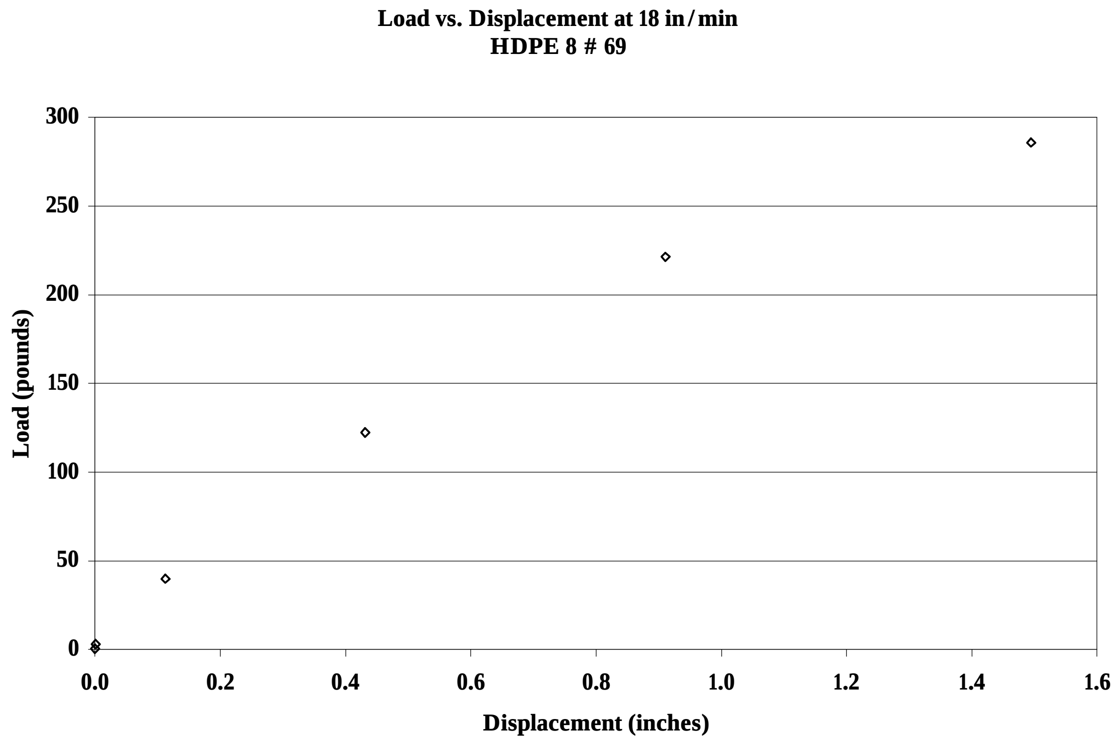


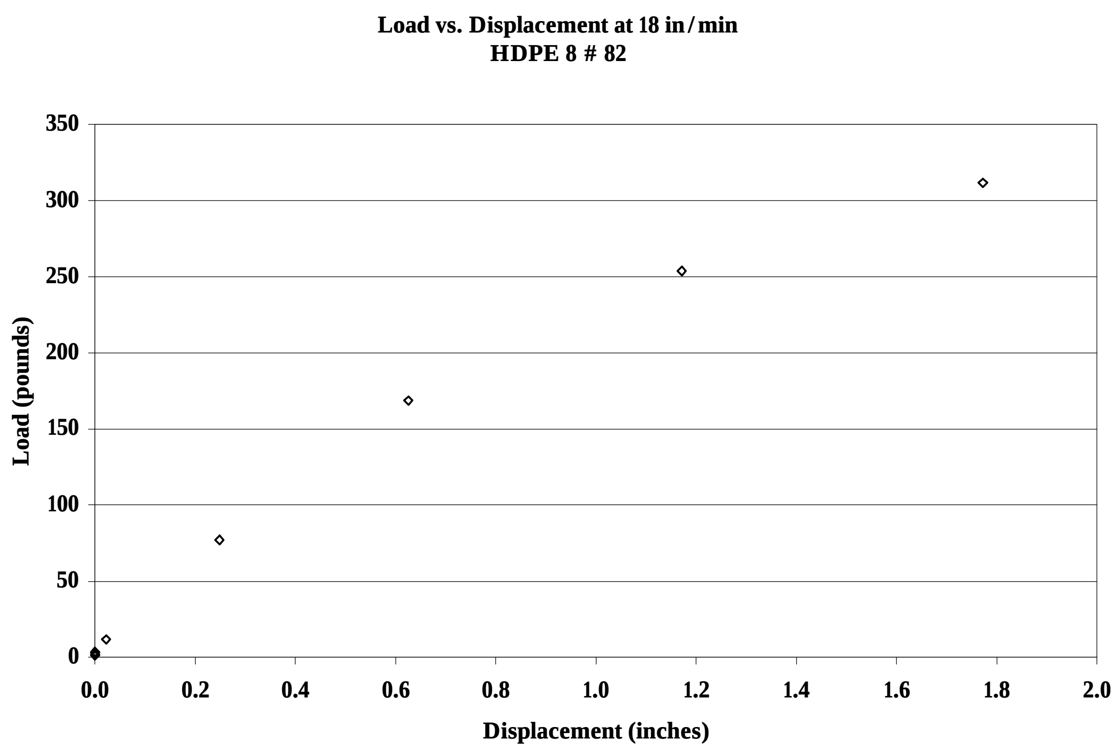
Load vs. Displacement at 10.0 in/min
HDPE 8 # 93



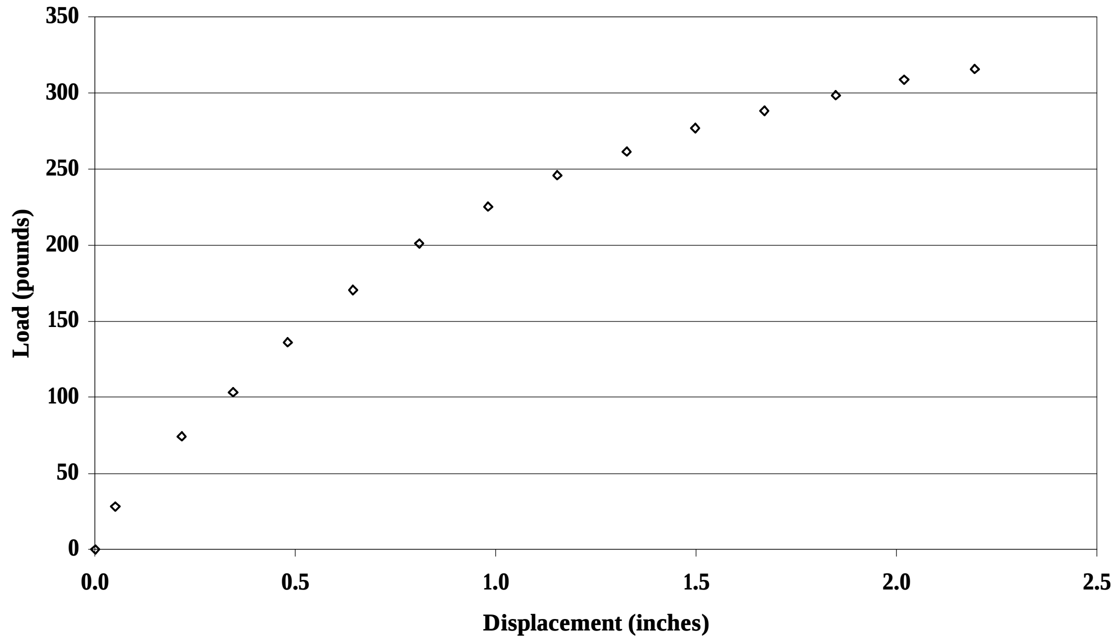
Load vs. Displacement at 18 in/min
HDPE 8 # 68



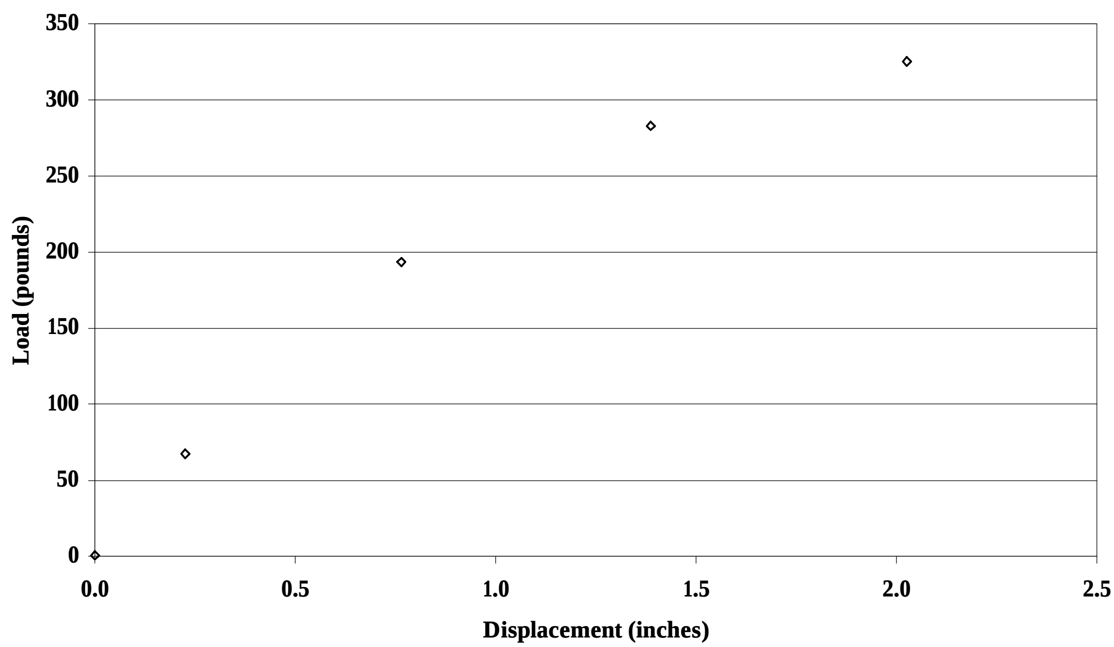

Load vs. Displacement at 18 in/min
HDPE 8 # 69
Load (pounds)
300
250
200
150
100
50
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Displacement (inches)


Load vs. Displacement at 18 in/min
HDPE 8 # 82
Load (pounds)
350
300
250
200
150
100
50
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Displacement (inches)

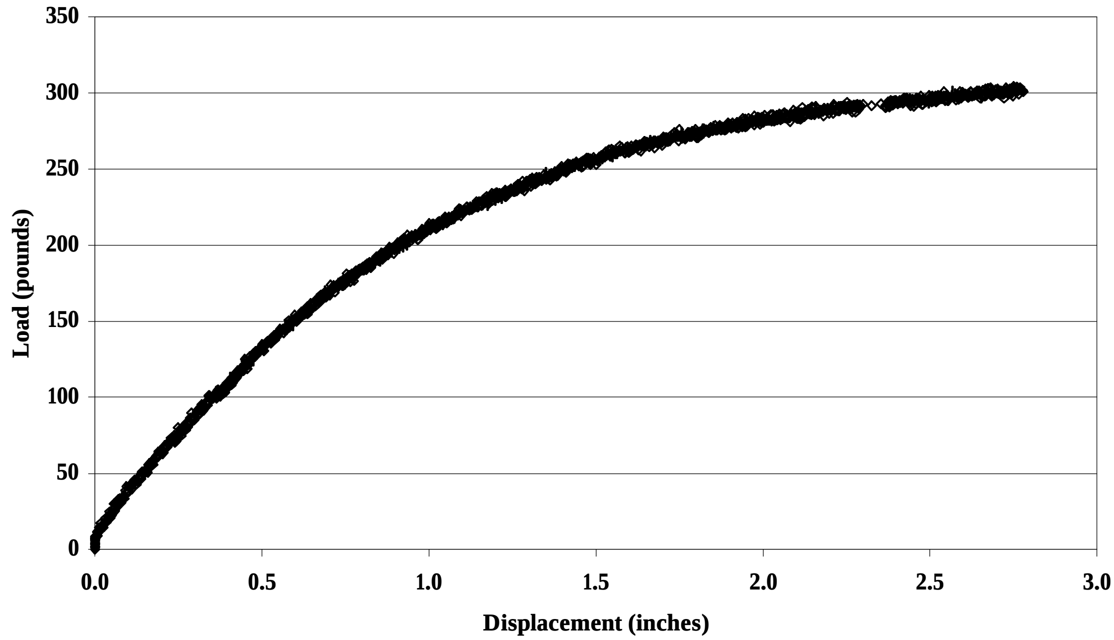
Load vs. Displacement at 18 in/min
HDPE 8 # 91



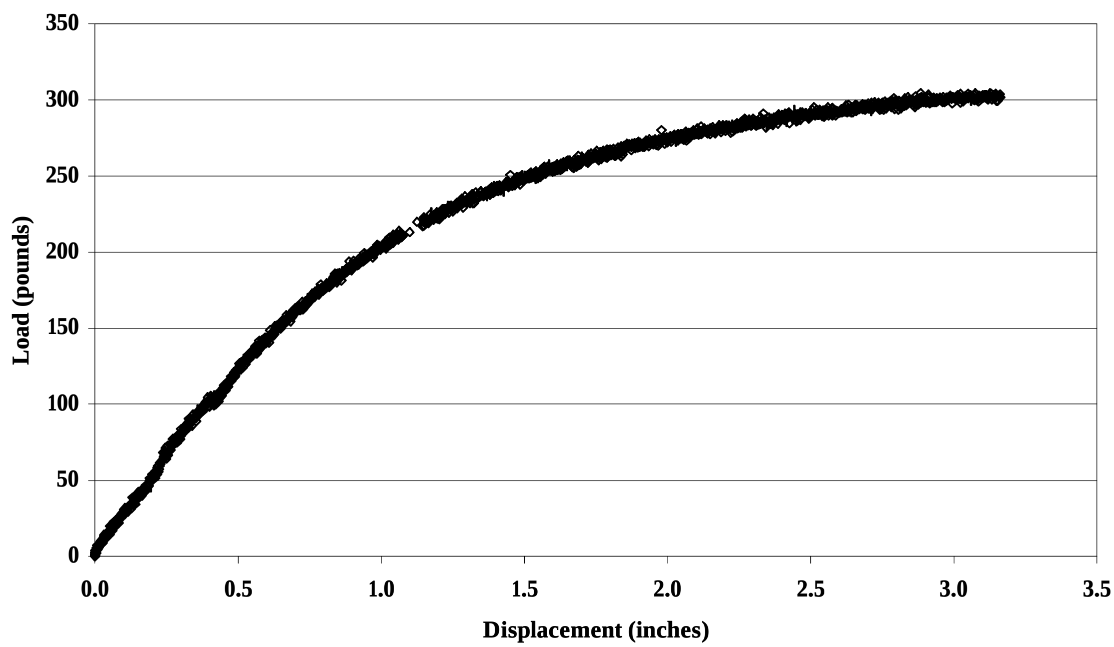
Load vs. Displacement at 18 in/min
HDPE 8 # 94

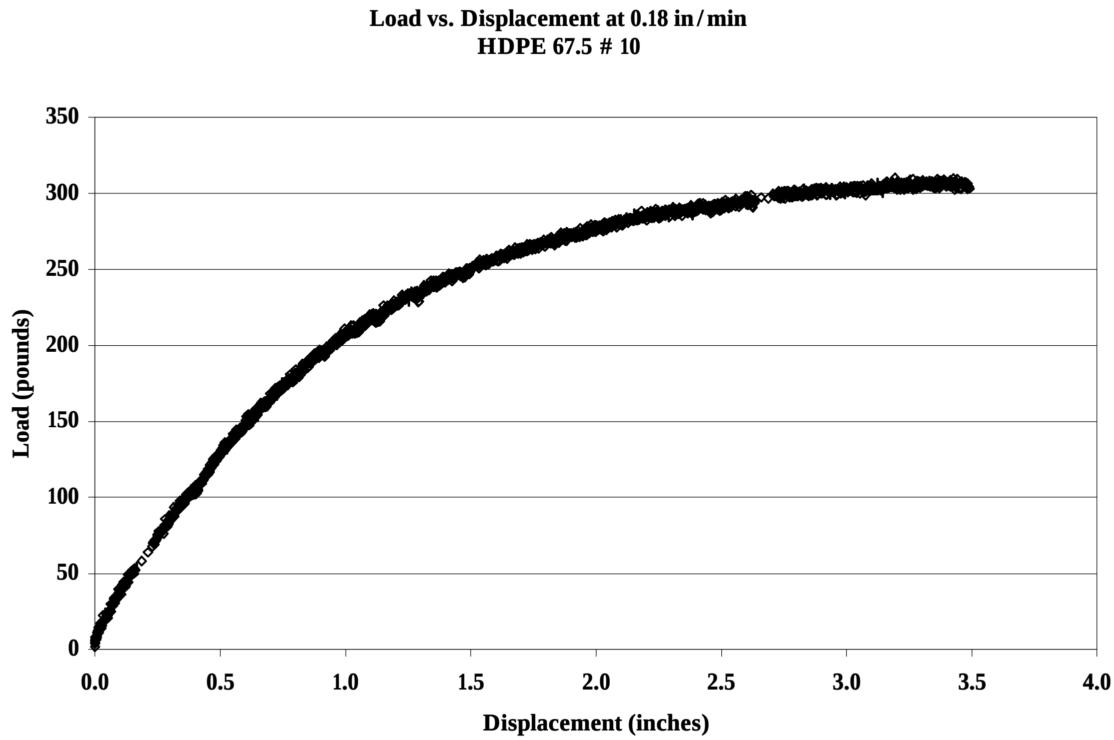


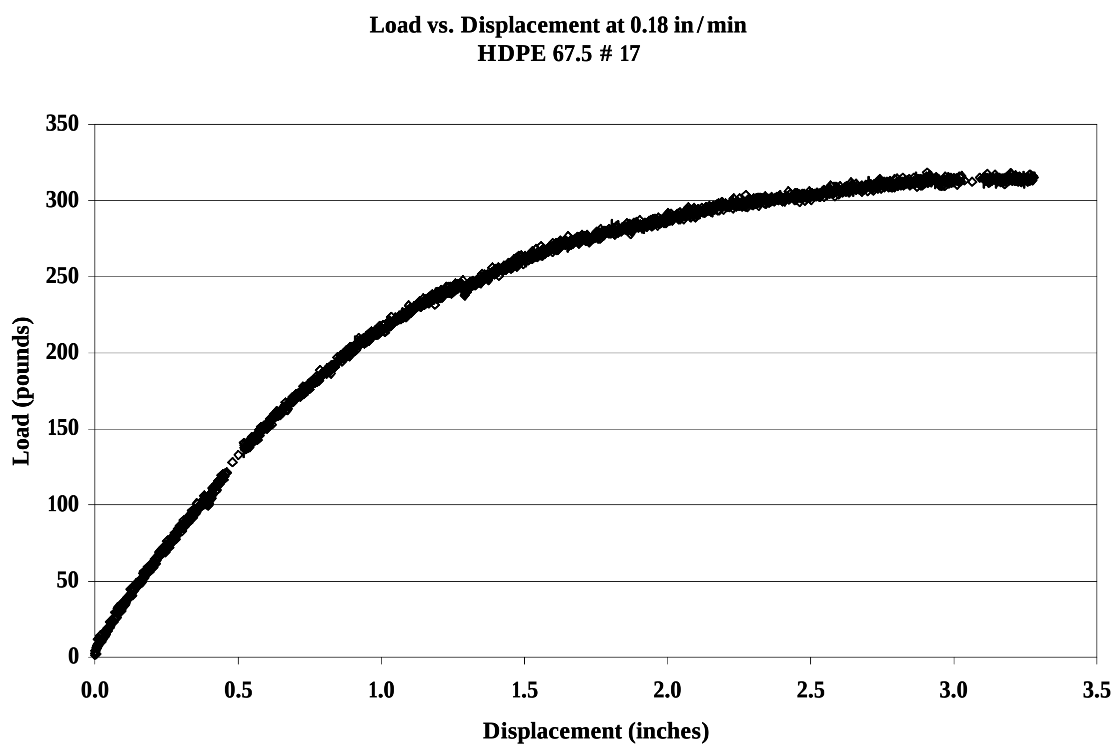
Load vs. Displacement at 0.18 in/min
HDPE 67.5 # 7



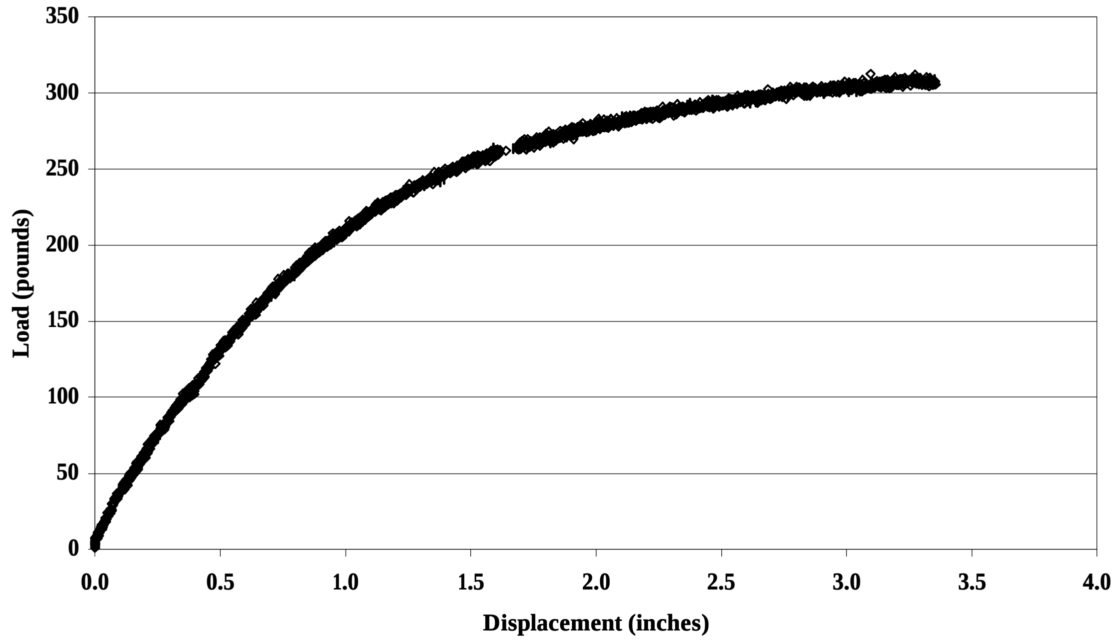
Load vs. Displacement at 0.18 in/min
HDPE 67.5 # 8



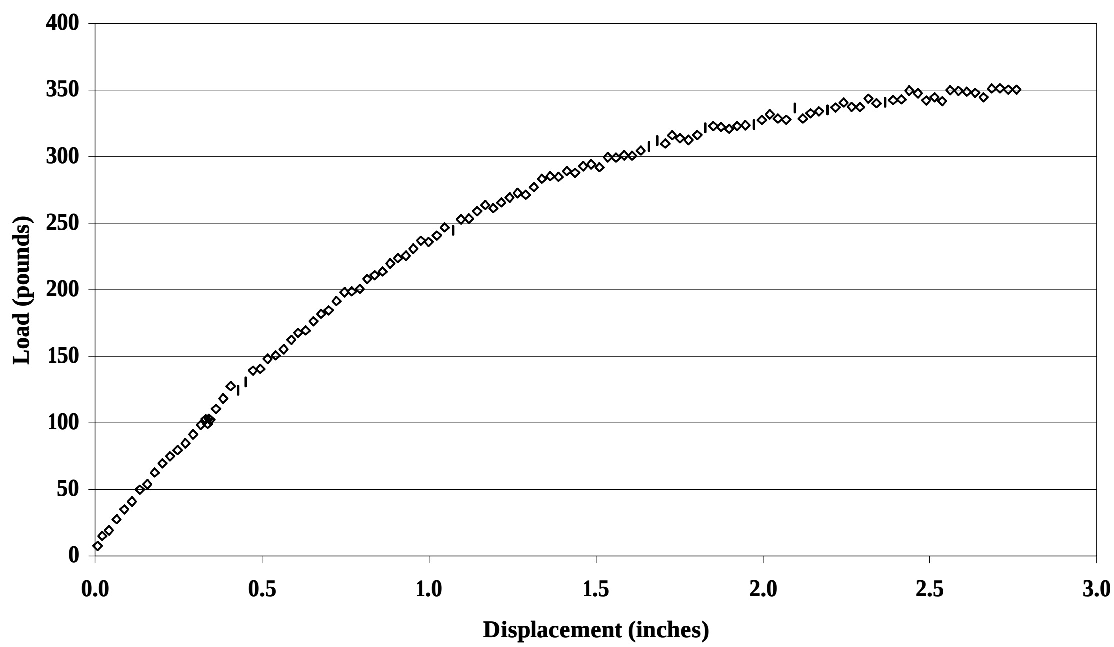

Load vs. Displacement at 0.18 in/min
HDPE 67.5 # 10
Load (pounds)
350
300
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Displacement (inches)

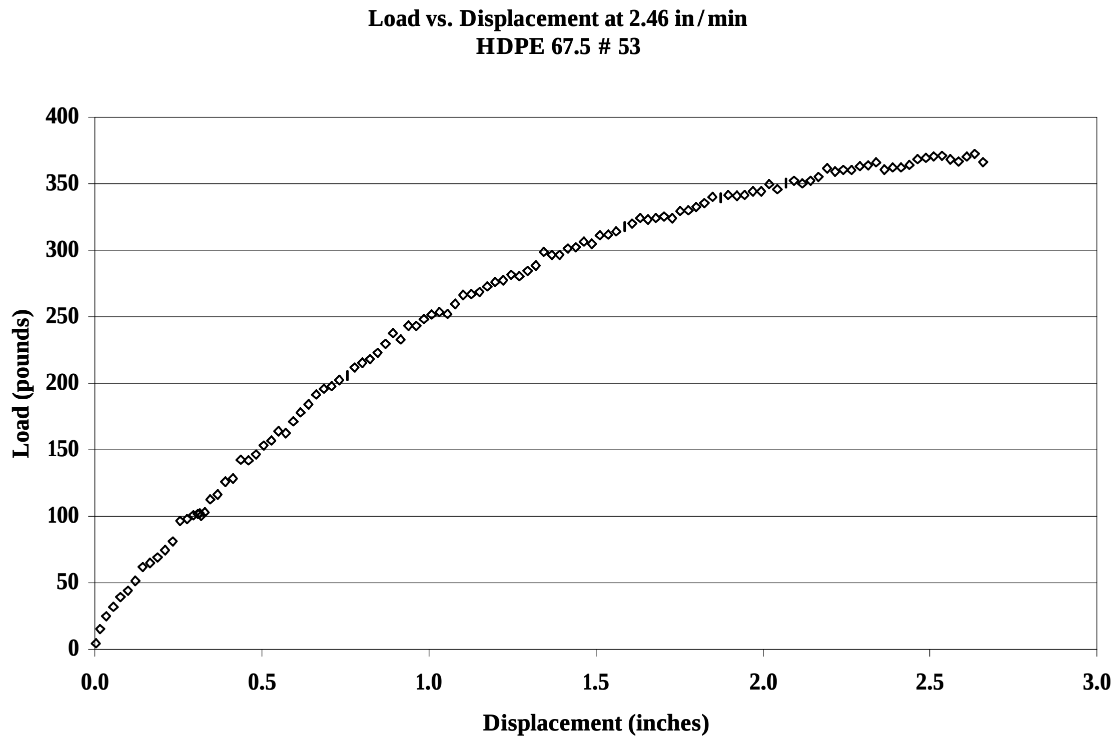

Load vs. Displacement at 0.18 in/min
HDPE 67.5 # 17
Load (pounds)
350
300
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Displacement (inches)

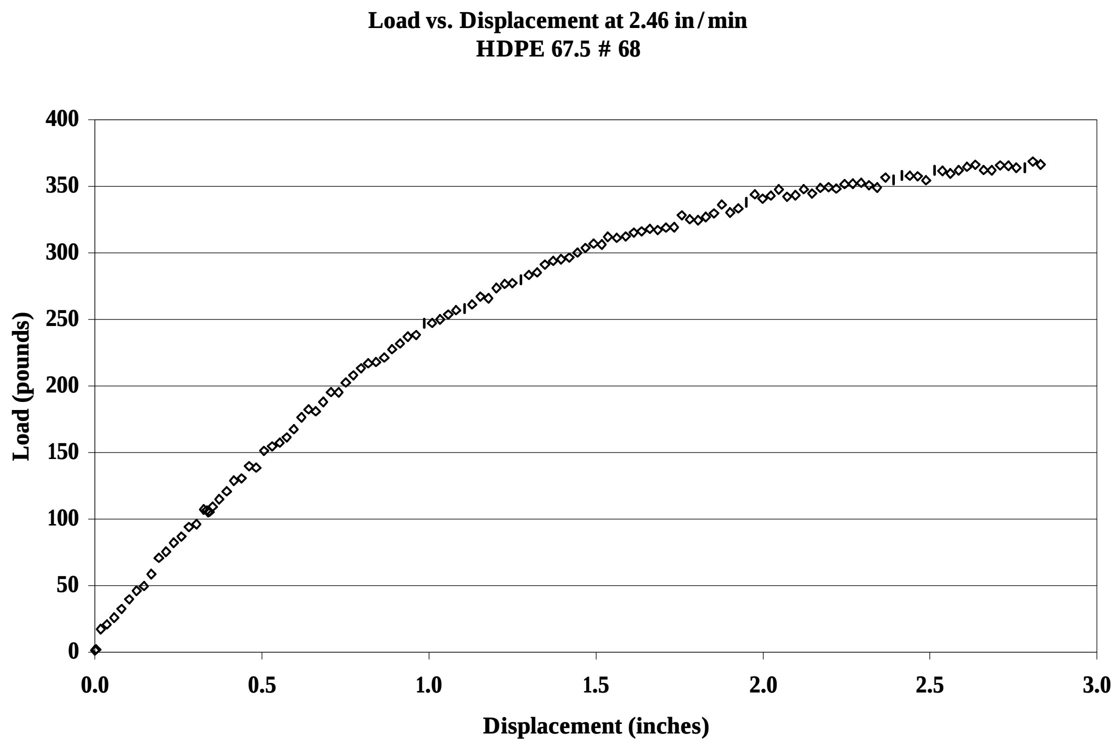
Load vs. Displacement at 0.18 in/min
HDPE 67.5 # 21



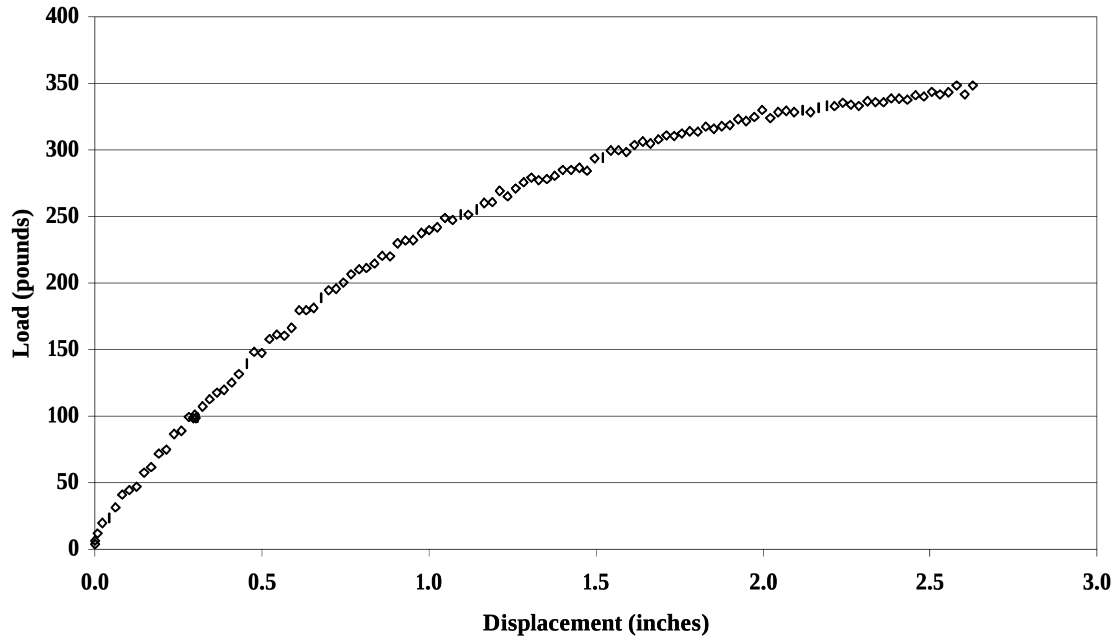
Load vs. Displacement at 2.46 in/min
HDPE 67.5 # 22



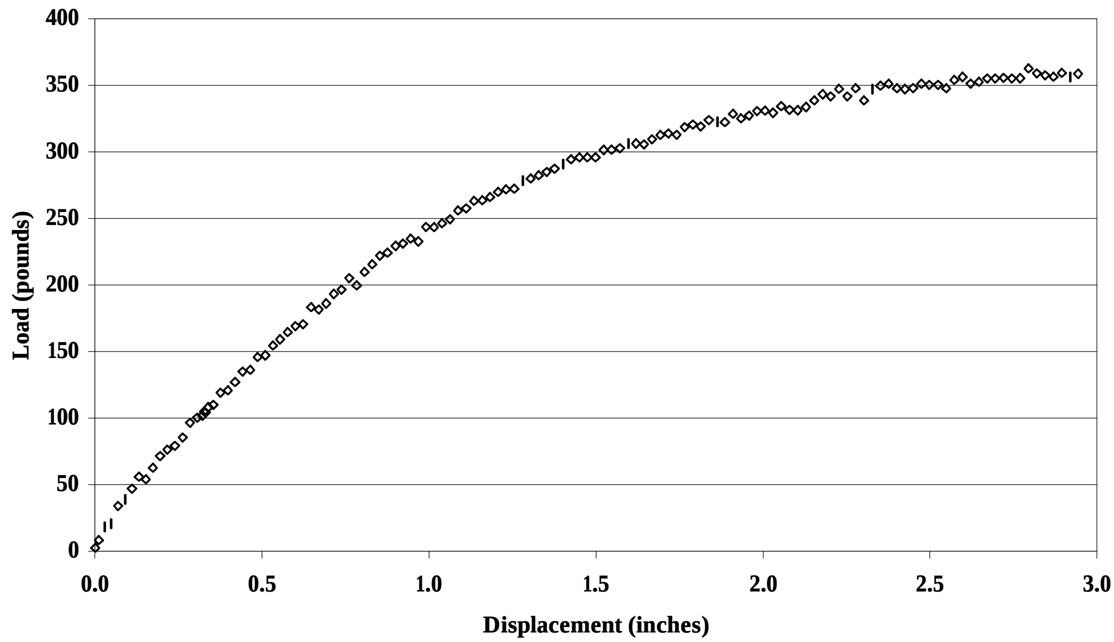

Load vs. Displacement at 2.46 in / min
HDPE 67.5 # 53
Load (pounds)
400
350
300
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Displacement (inches)


Load vs. Displacement at 2.46 in / min
HDPE 67.5 # 68
Load (pounds)
400
350
300
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Displacement (inches)

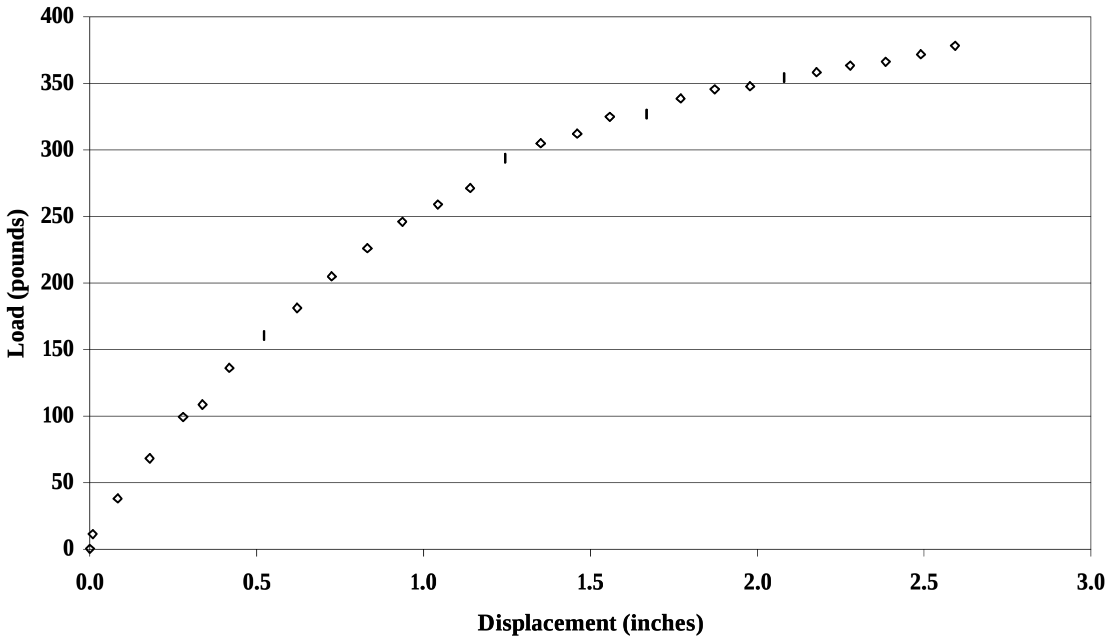
Load vs. Displacement at 2.46 in / min
HDPE 67.5 # 70



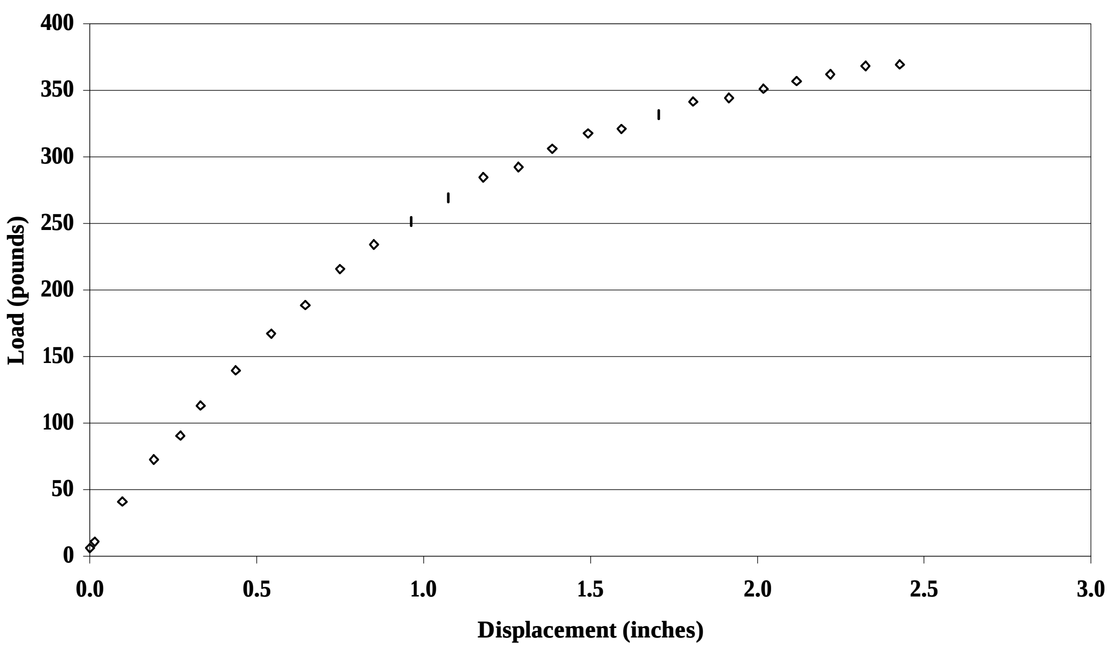
Load vs. Displacement at 2.46 in / min
HDPE 67.5 # 79

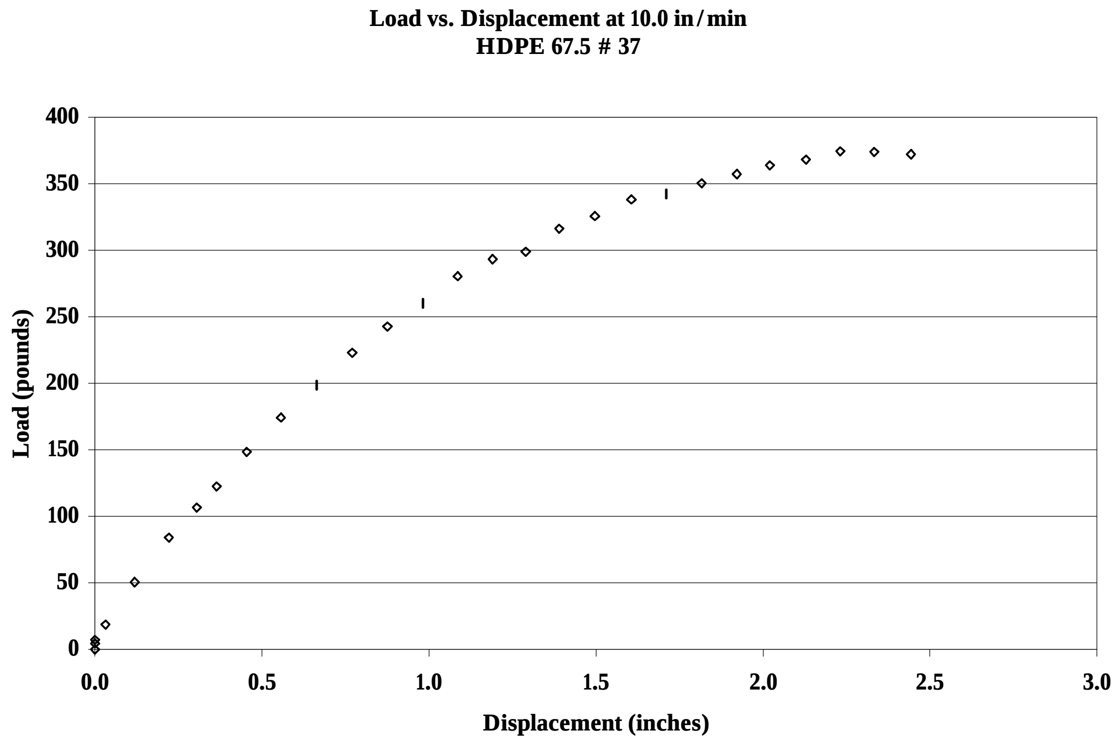


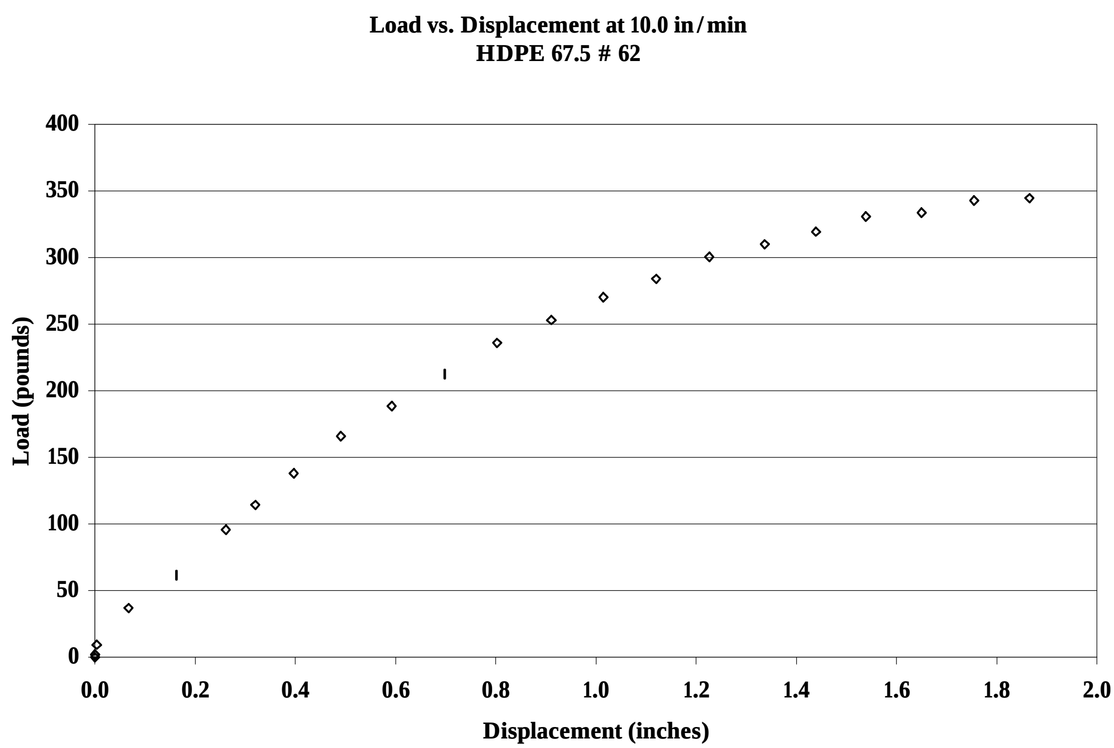
Load vs. Displacement at 10.0 in/min
HDPE 67.5 # 11



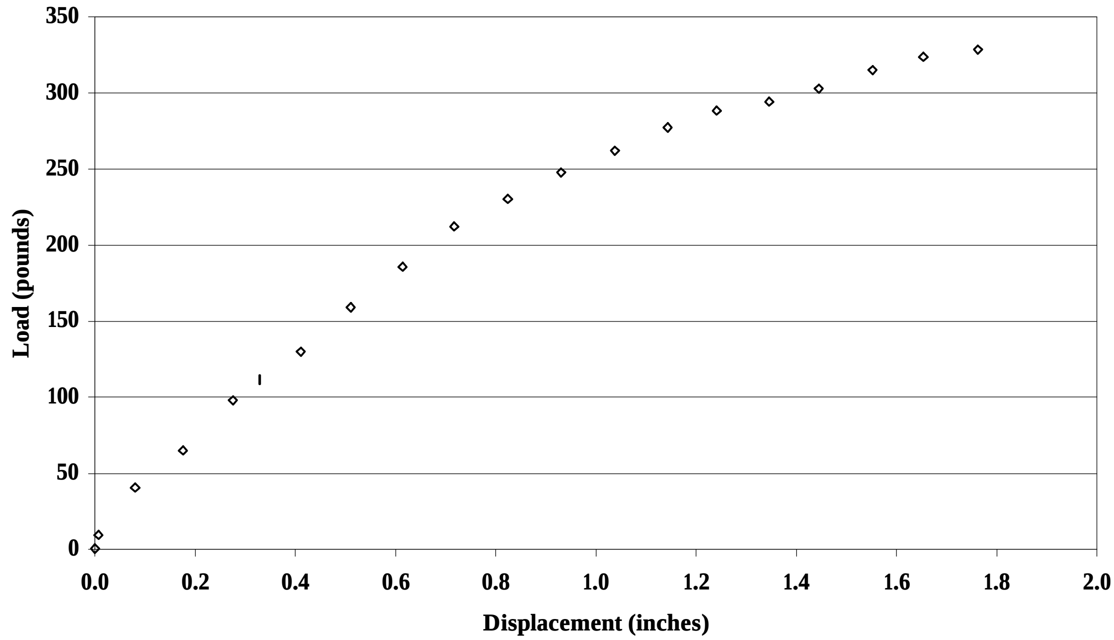
Load vs. Displacement at 10.0 in/min
HDPE 67.5 # 19



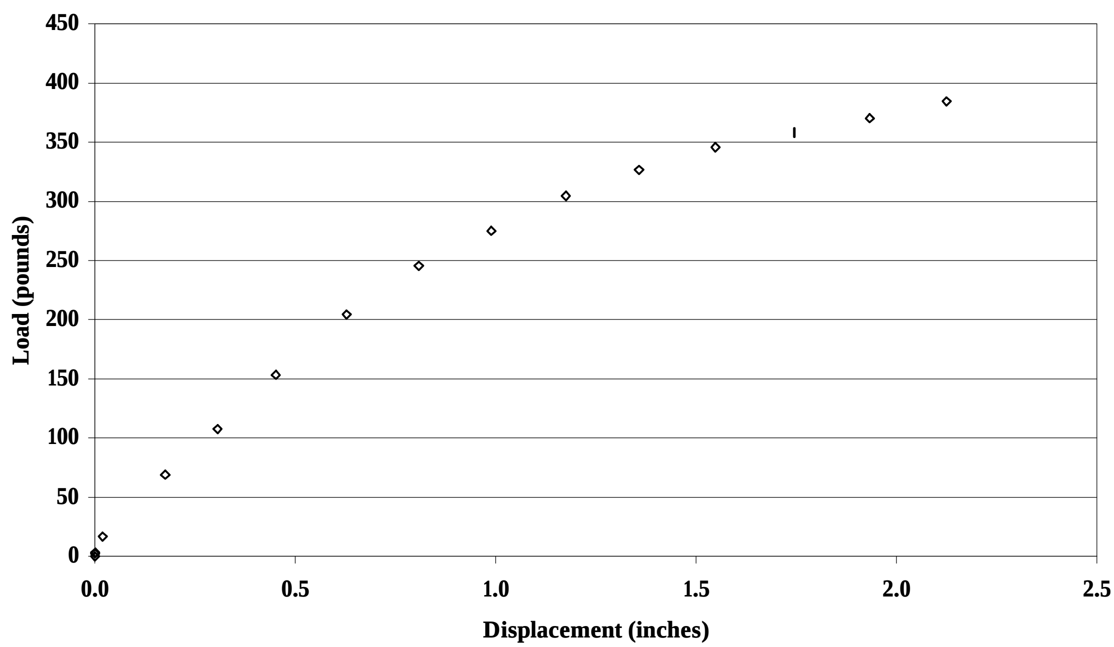

Load vs. Displacement at 10.0 in/min
HDPE 67.5 # 37
Load (pounds)
400
350
300
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Displacement (inches)

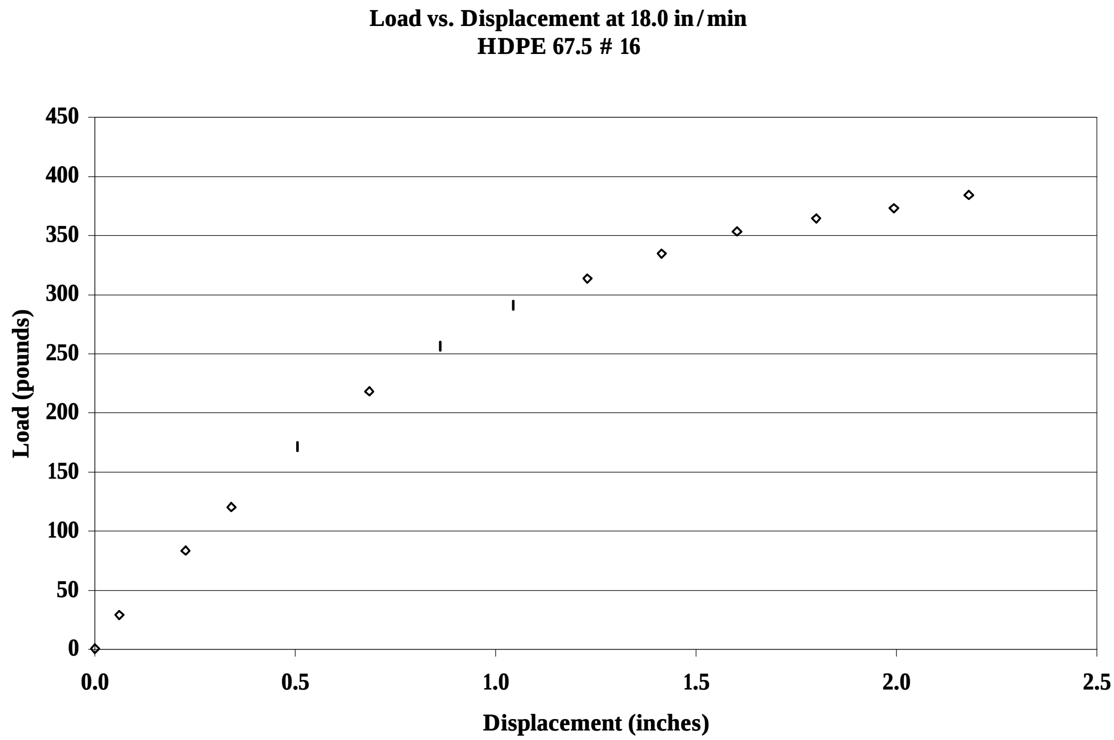

Load vs. Displacement at 10.0 in/min
HDPE 67.5 # 62
Load (pounds)
400
350
300
250
200
150
100
50
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Displacement (inches)

Load vs. Displacement at 10.0 in/min
HDPE 67.5 # 68

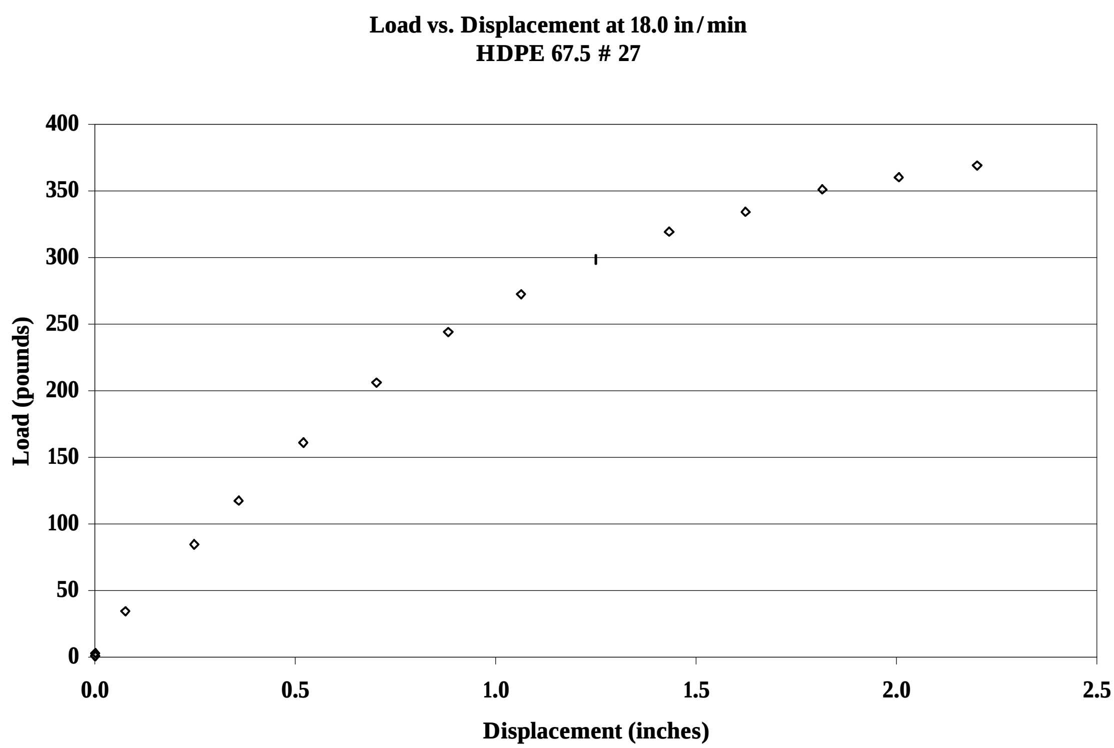


Load vs. Displacement at 18.0 in/min
HDPE 67.5 # 5



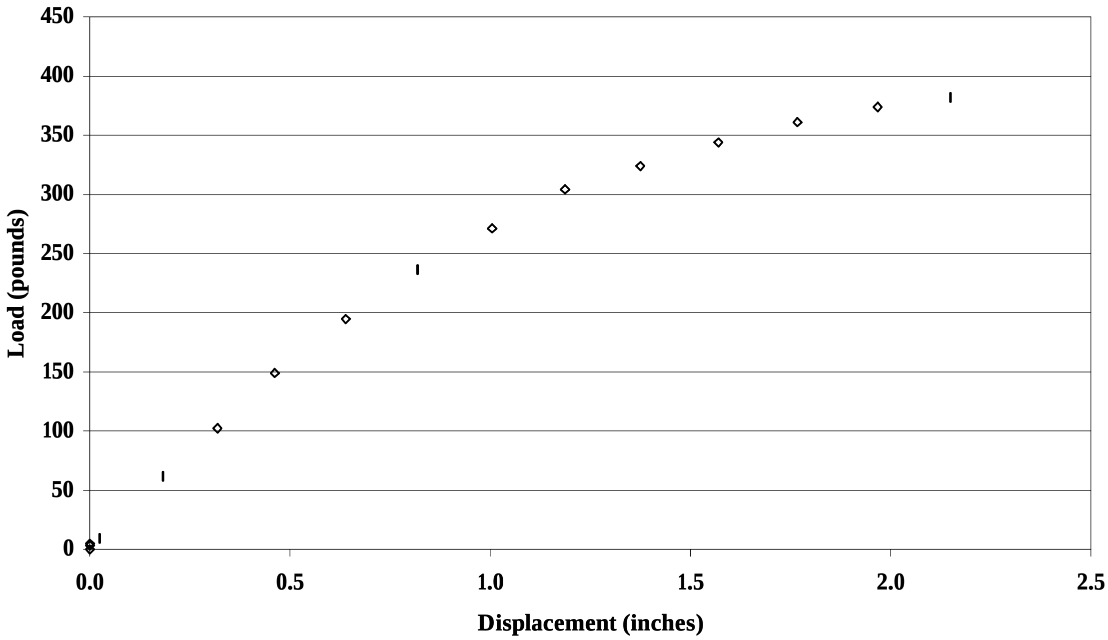


Load vs. Displacement at 18.0 in/min
HDPE 67.5 # 16
Load (pounds)
450
400
350
300
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
2.5
Displacement (inches)

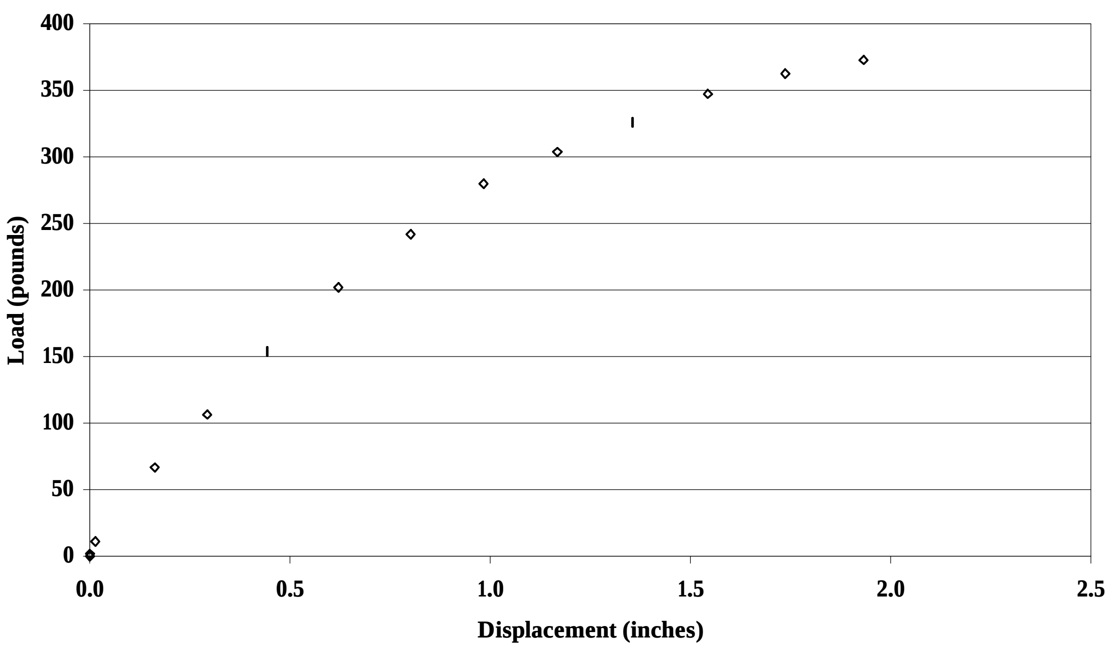


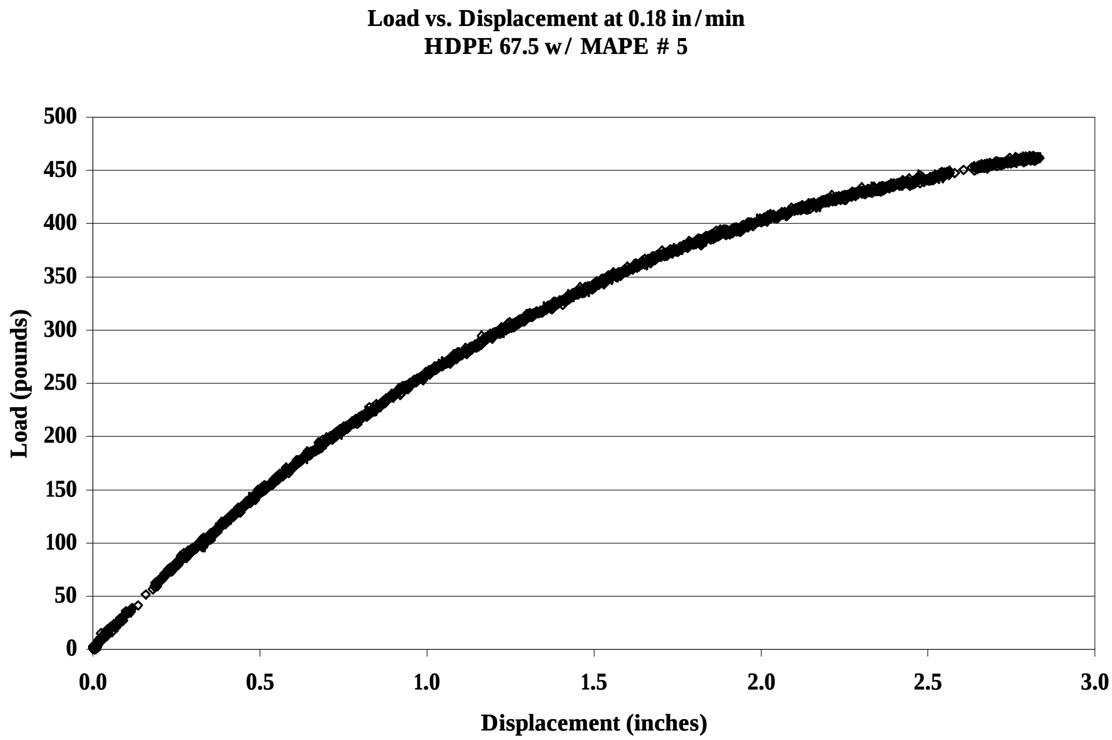
Load vs. Displacement at 18.0 in/min
HDPE 67.5 # 27
Load (pounds)
400
350
300
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
2.5
Displacement (inches)

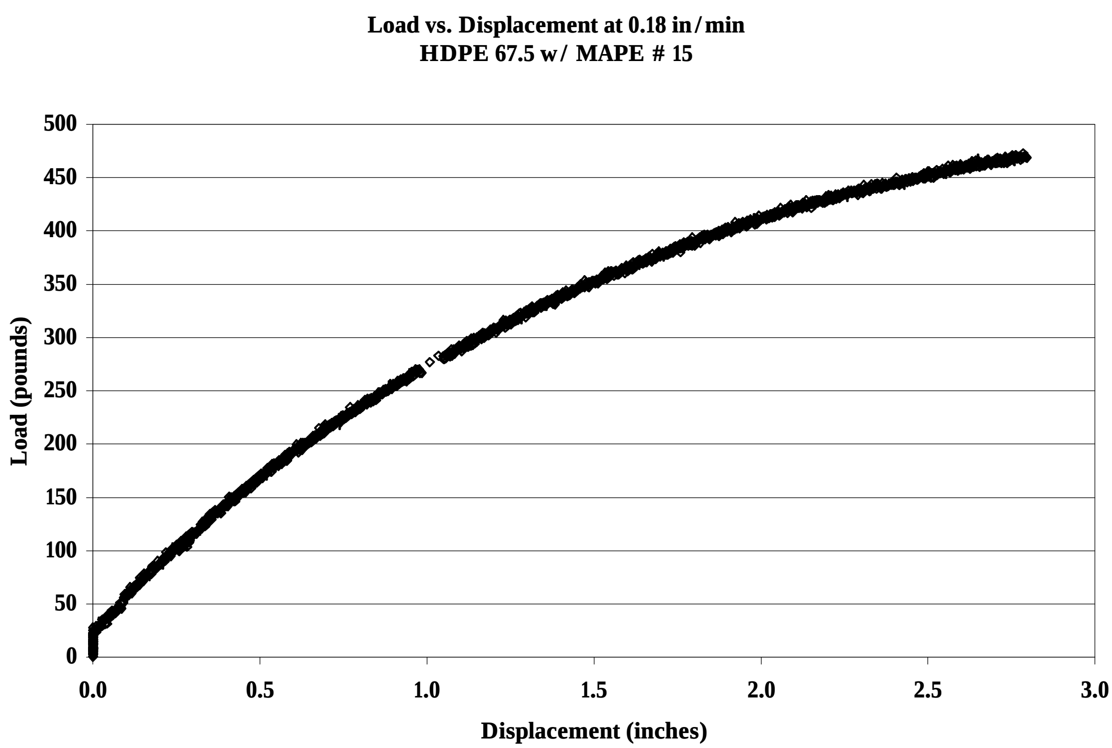
Load vs. Displacement at 18.0 in / min
HDPE 67.5 # 57



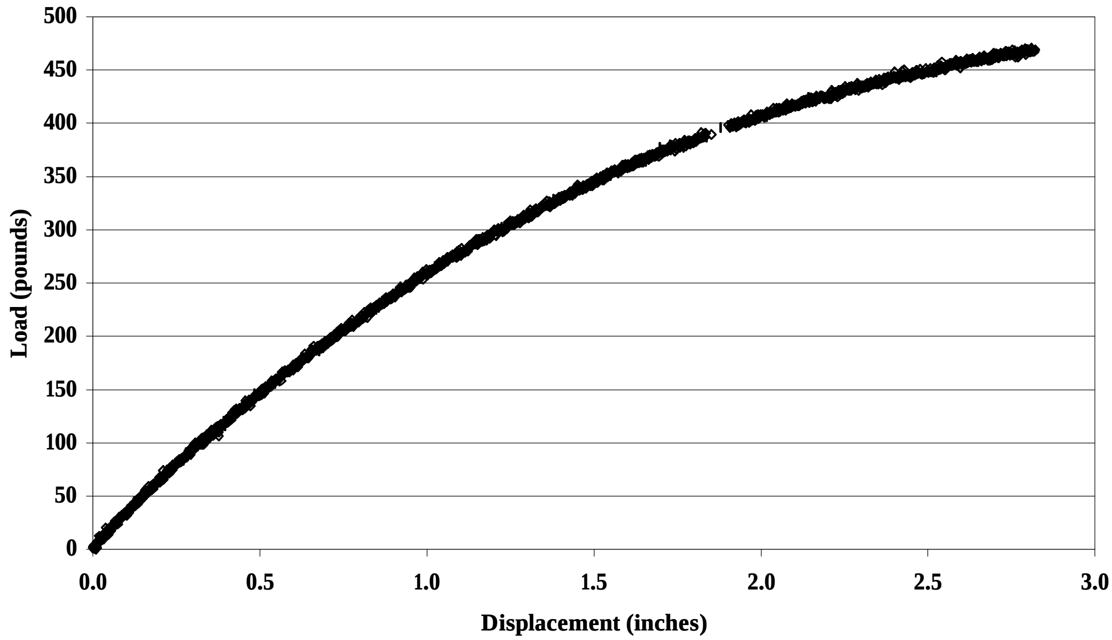
Load vs. Displacement at 18.0 in / min
HDPE 67.5 # 67



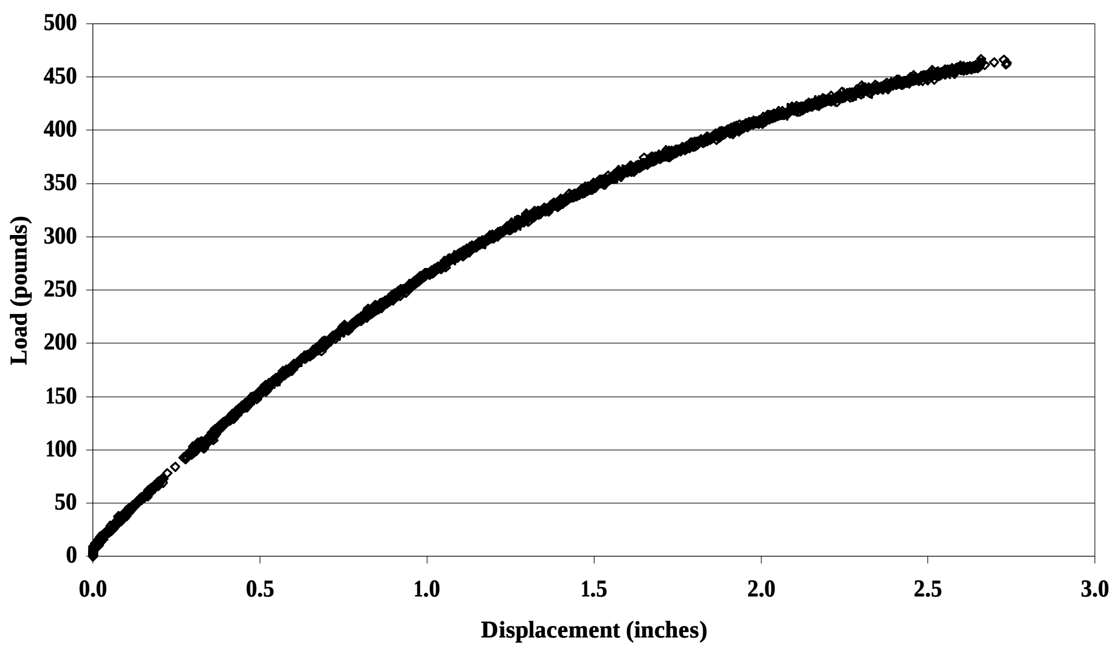

Load vs. Displacement at 0.18 in/min
HDPE 67.5 w/ MAPE # 5
Load (pounds)
0
50
100
150
200
250
300
350
400
450
500
Displacement (inches)
0.0
0.5
1.0
1.5
2.0
2.5
3.0


Load vs. Displacement at 0.18 in/min
HDPE 67.5 w/ MAPE # 15
Load (pounds)
0
50
100
150
200
250
300
350
400
450
500
Displacement (inches)
0.0
0.5
1.0
1.5
2.0
2.5
3.0

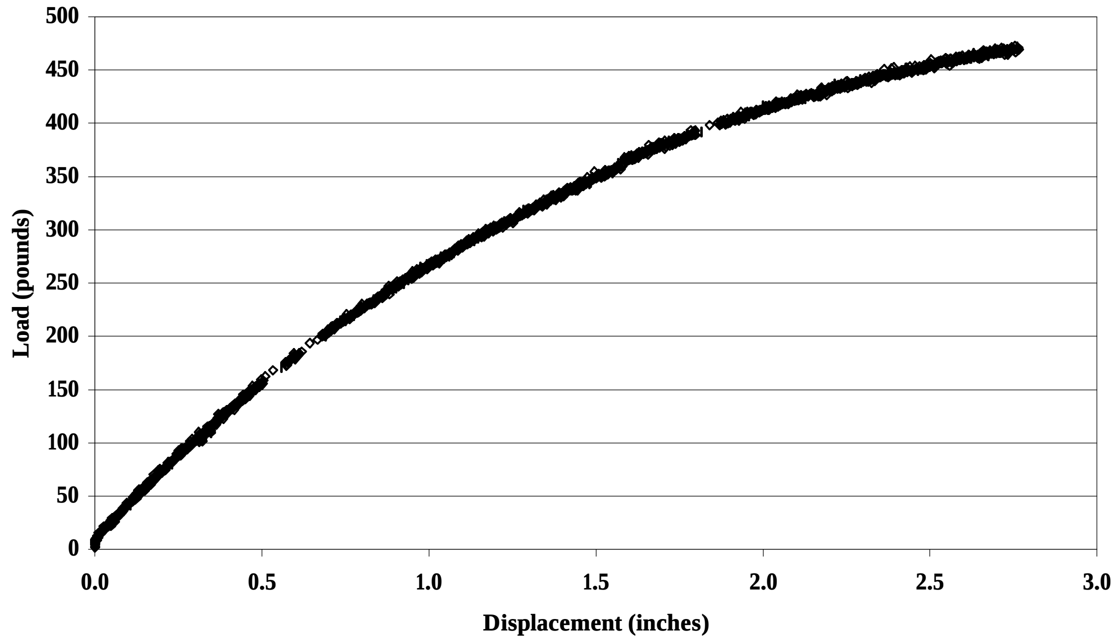
Load vs. Displacement at 0.18 in/min
HDPE 67.5 w/ MAPE # 16



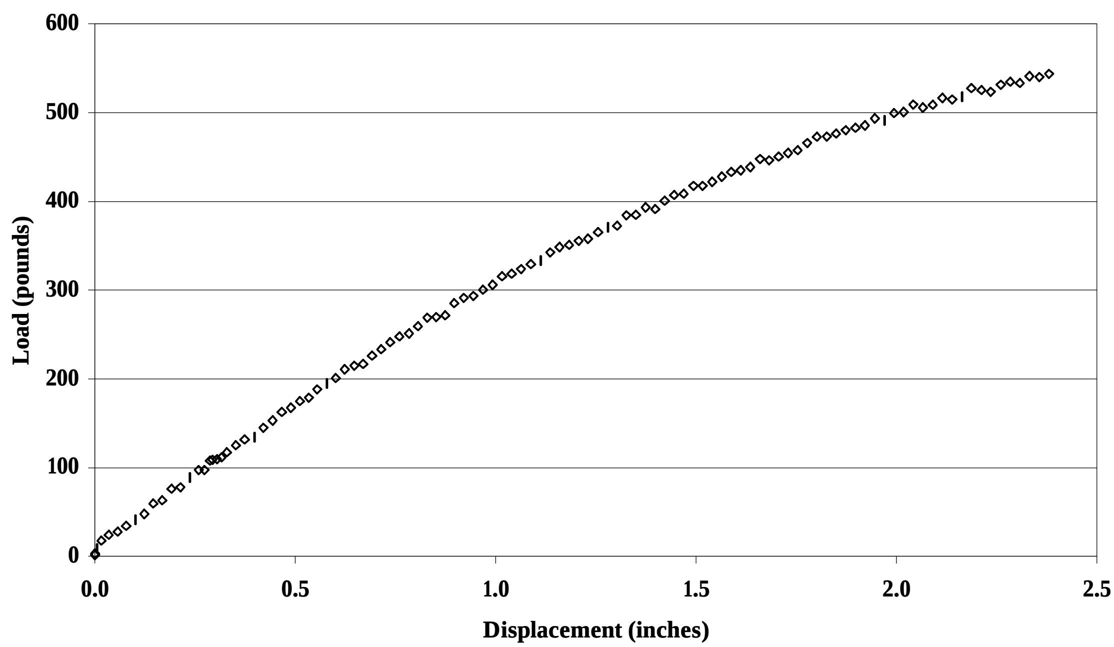
Load vs. Displacement at 0.18 in/min
HDPE 67.5 w/ MAPE # 25



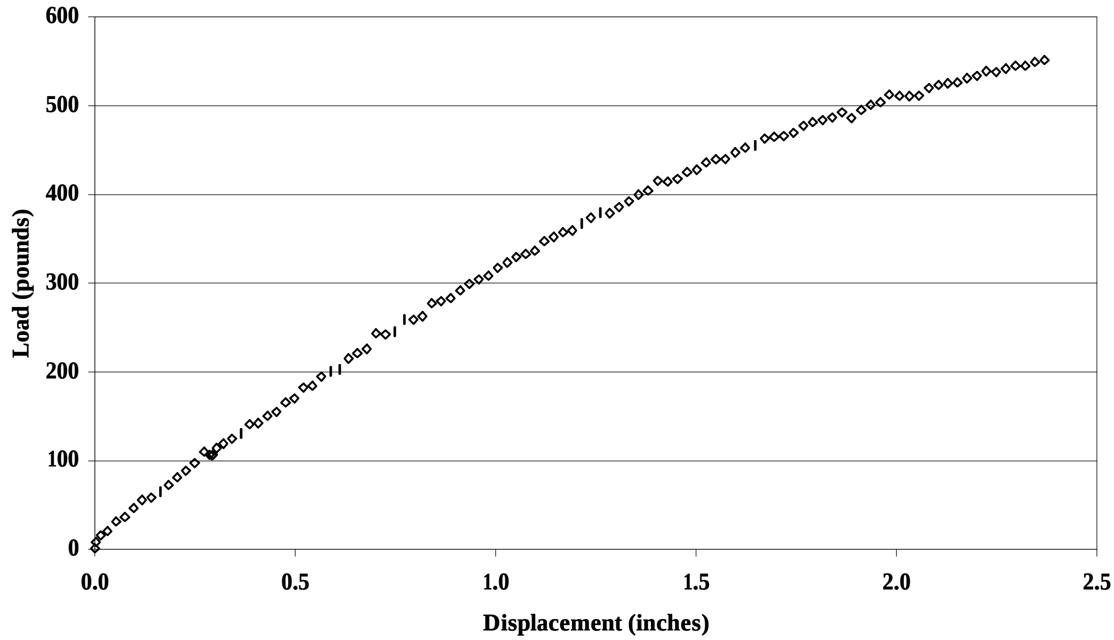
Load vs. Displacement at 0.18 in/min
HDPE 67.5 w/ MAPE # 55



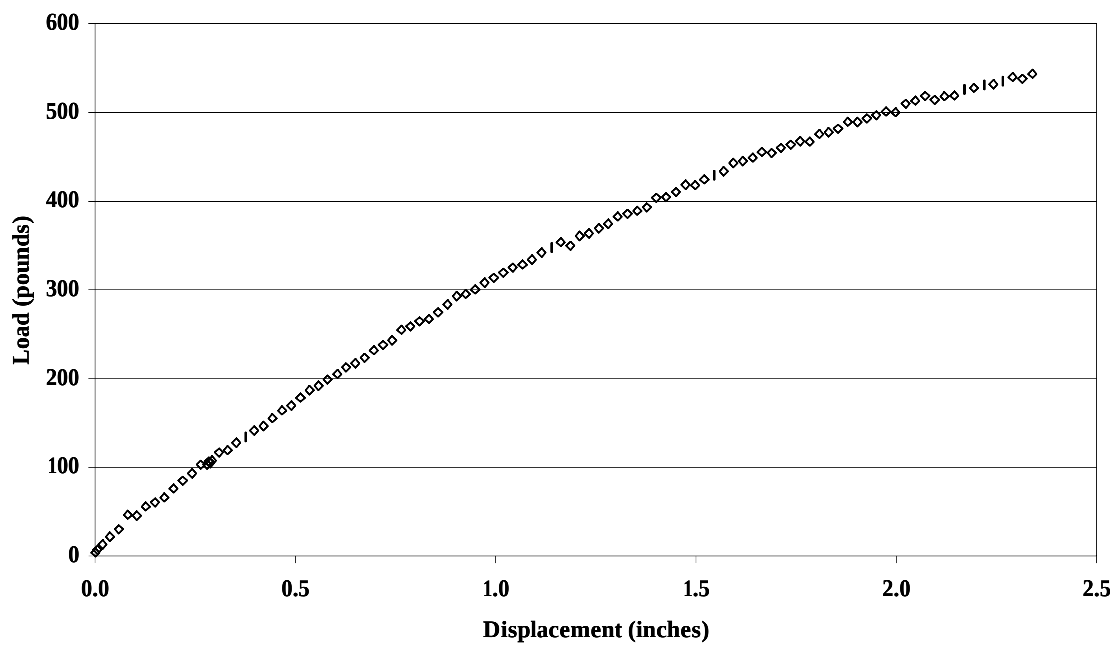
Load vs. Displacement at 2.46 in/min
HDPE 67.5 w/MAPE # 2



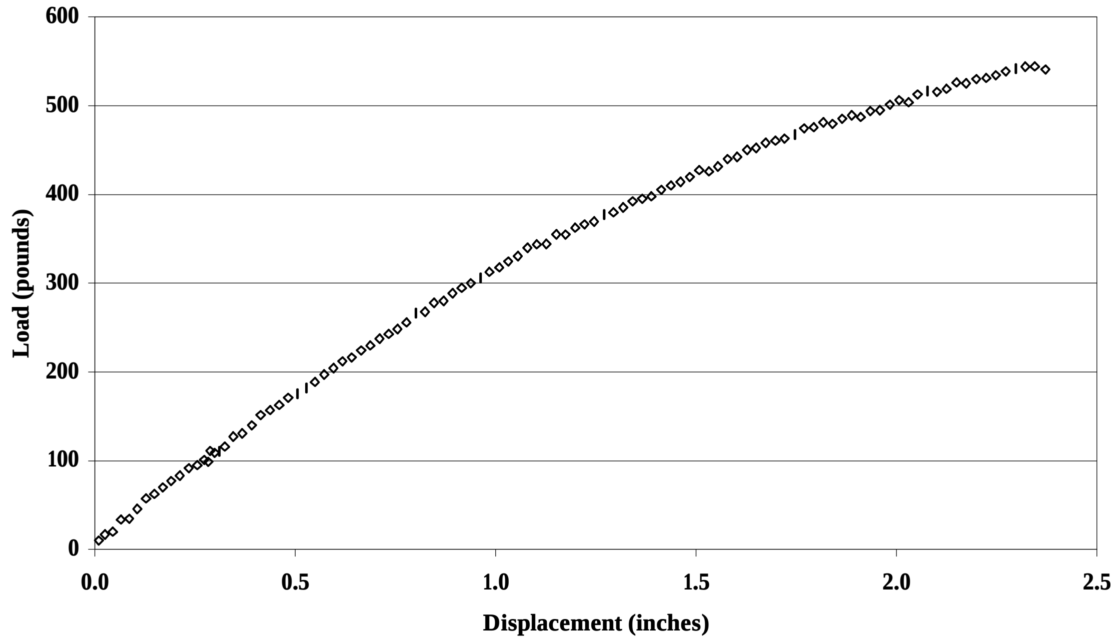
Load vs. Displacement at 2.46 in/min
HDPE 67.5 w/MAPE # 22



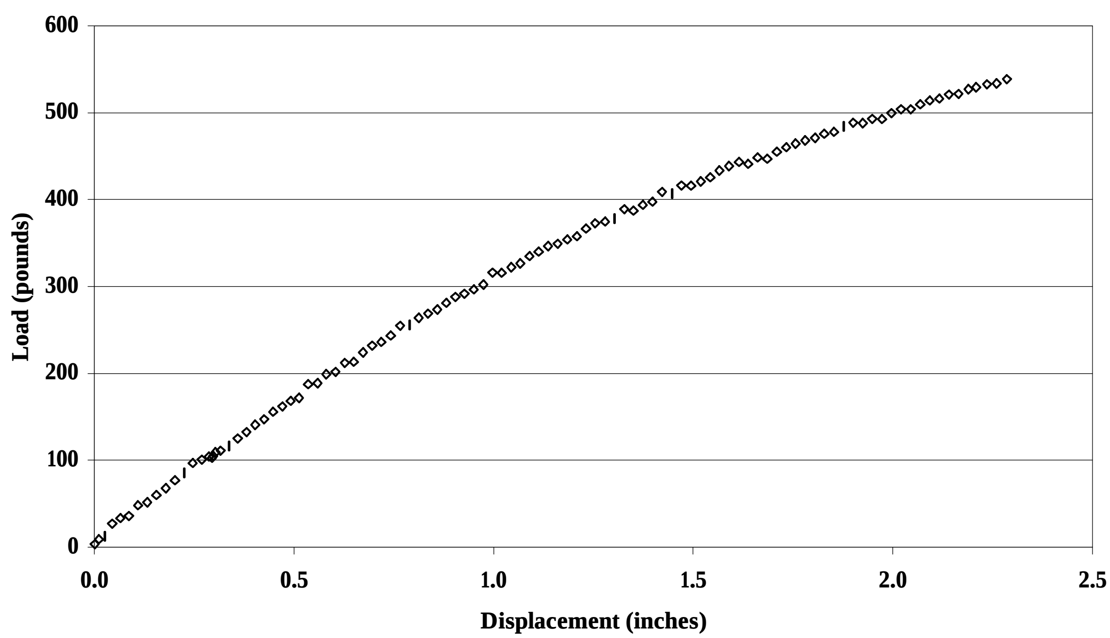
Load vs. Displacement at 2.46 in/min
HDPE 67.5 w/MAPE # 61

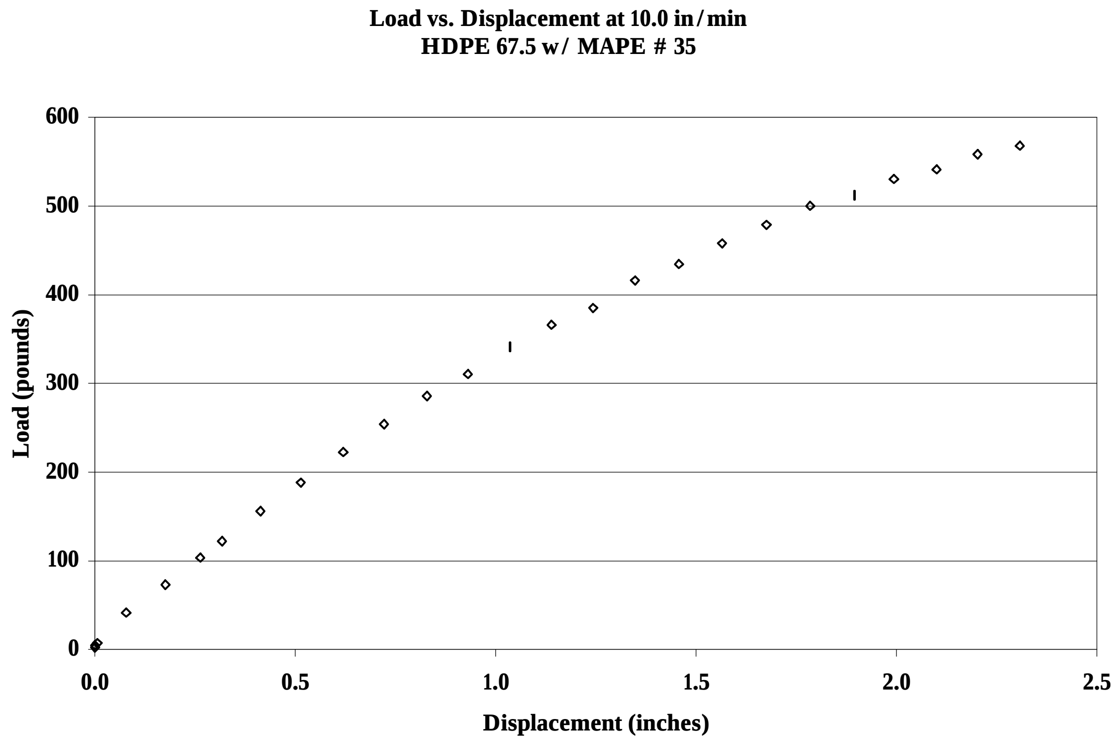


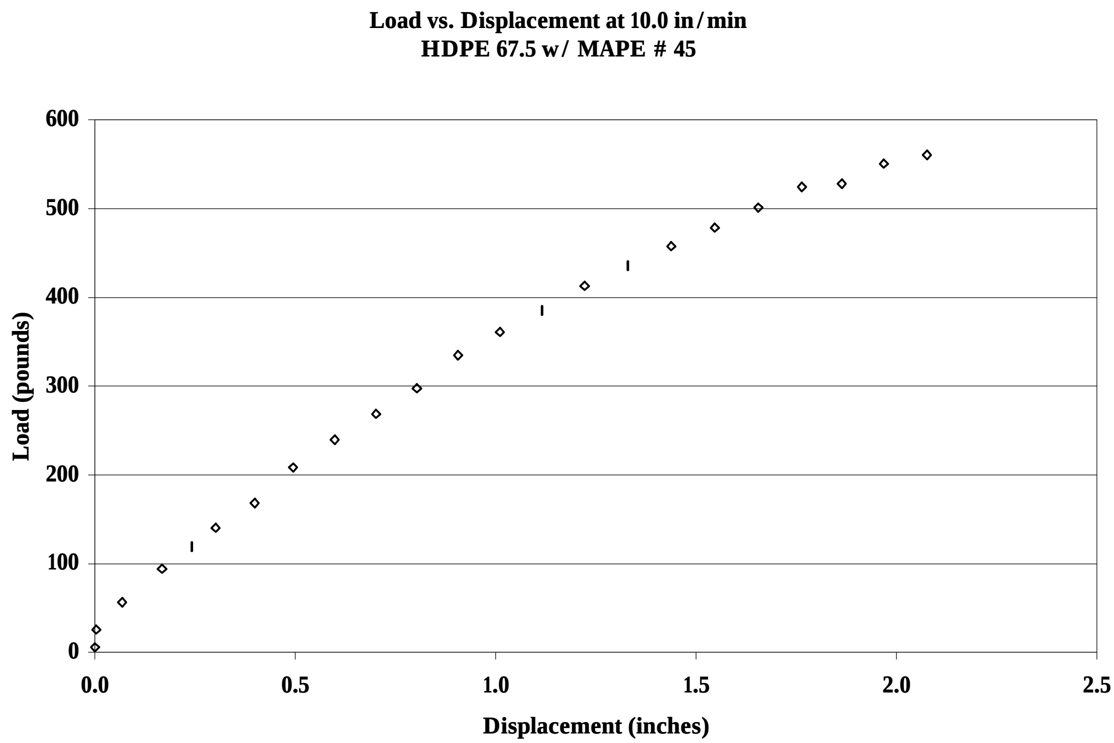
Load vs. Displacement at 2.46 in/min
HDPE 67.5 w/MAPE # 62



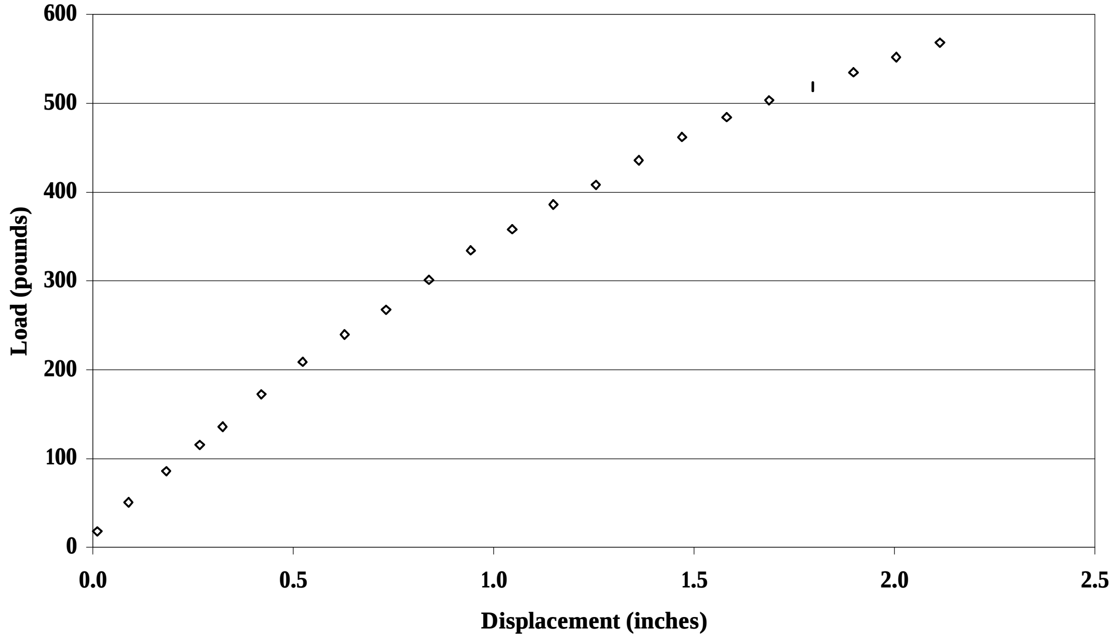
Load vs. Displacement at 2.46 in/min
HDPE 67.5 w/MAPE # 64



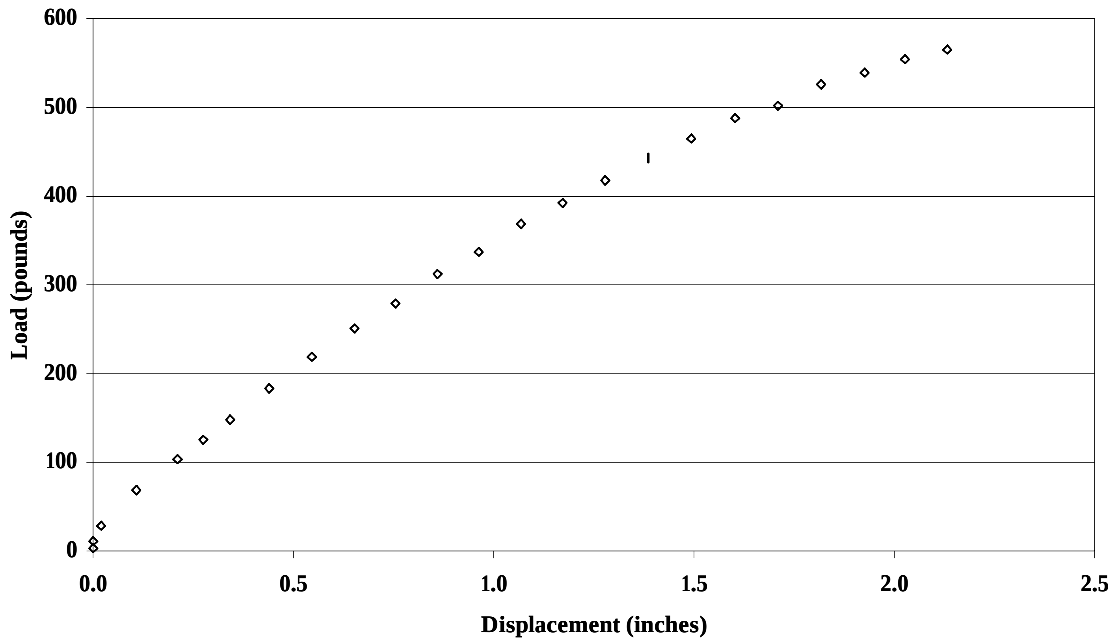

Load vs. Displacement at 10.0 in/min
HDPE 67.5 w/ MAPE # 35
Load (pounds)
600
500
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
Displacement (inches)

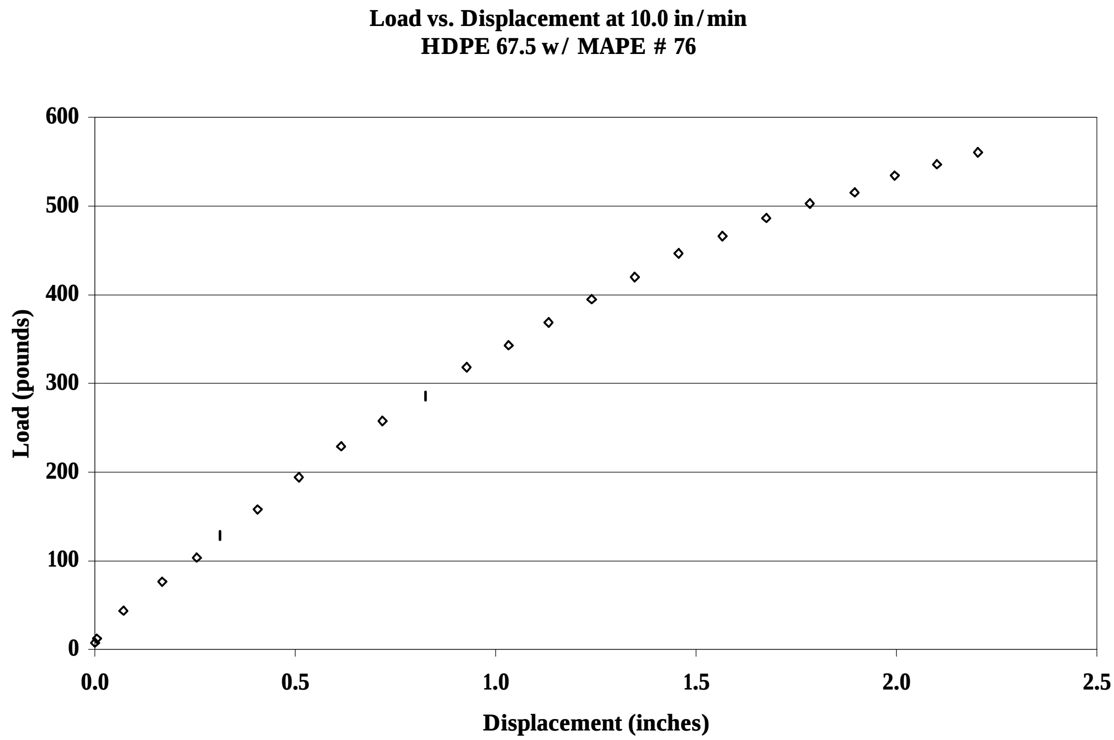

Load vs. Displacement at 10.0 in/min
HDPE 67.5 w/ MAPE # 45
Load (pounds)
600
500
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
Displacement (inches)

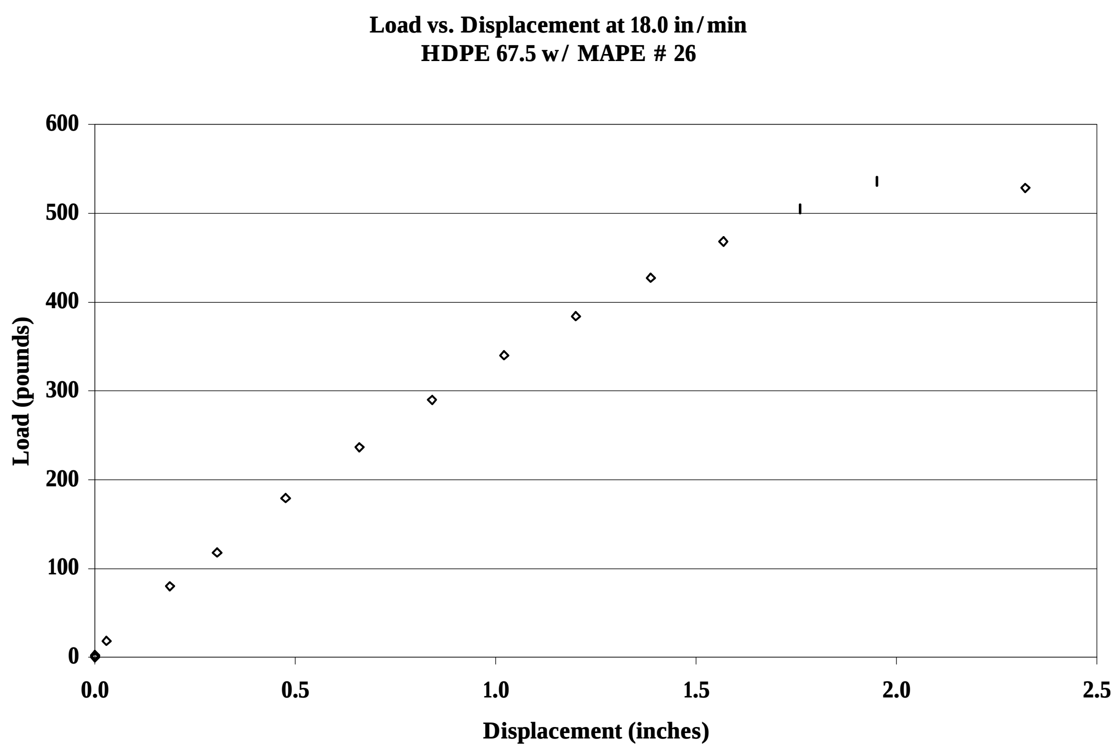
Load vs. Displacement at 10.0 in/min
HDPE 67.5 w/ MAPE # 46

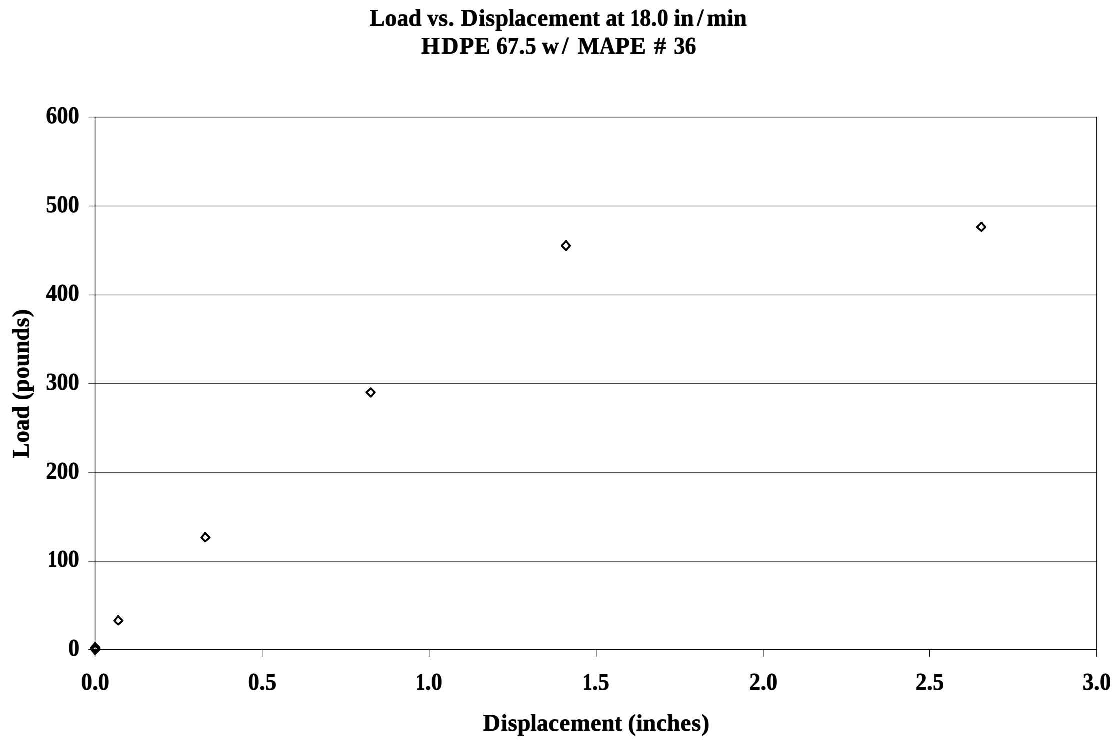


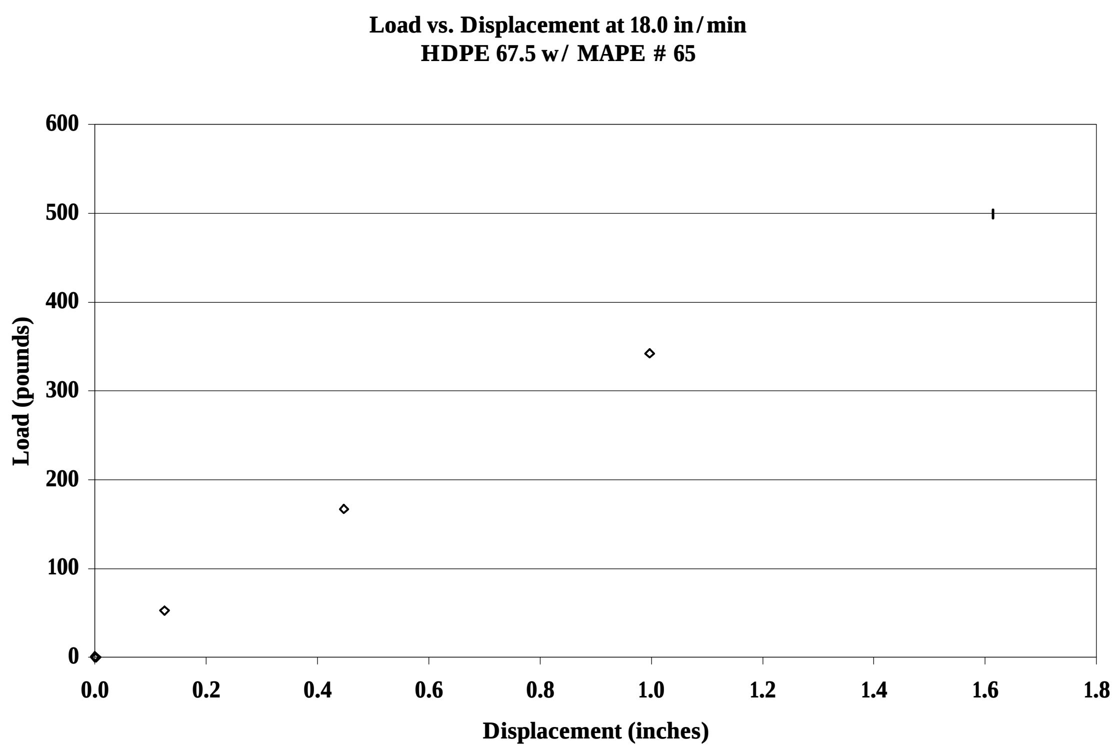
Load vs. Displacement at 10.0 in/min
HDPE 67.5 w/ MAPE # 56



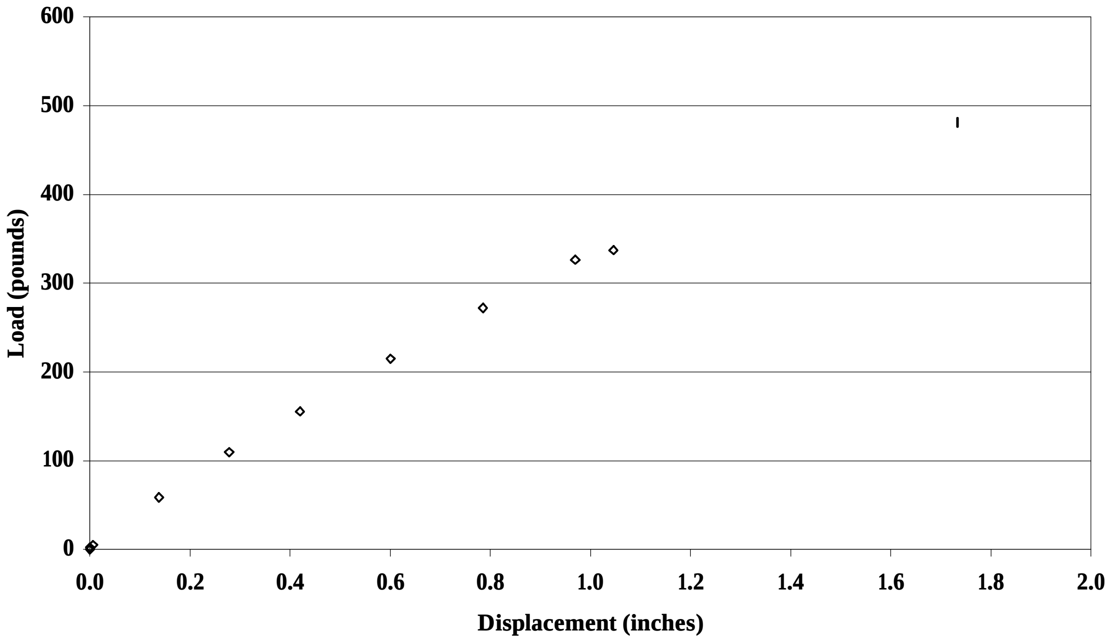

Load vs. Displacement at 10.0 in/min
HDPE 67.5 w/ MAPE # 76
Load (pounds)
600
500
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
Displacement (inches)


Load vs. Displacement at 18.0 in/min
HDPE 67.5 w/ MAPE # 26
Load (pounds)
600
500
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
Displacement (inches)

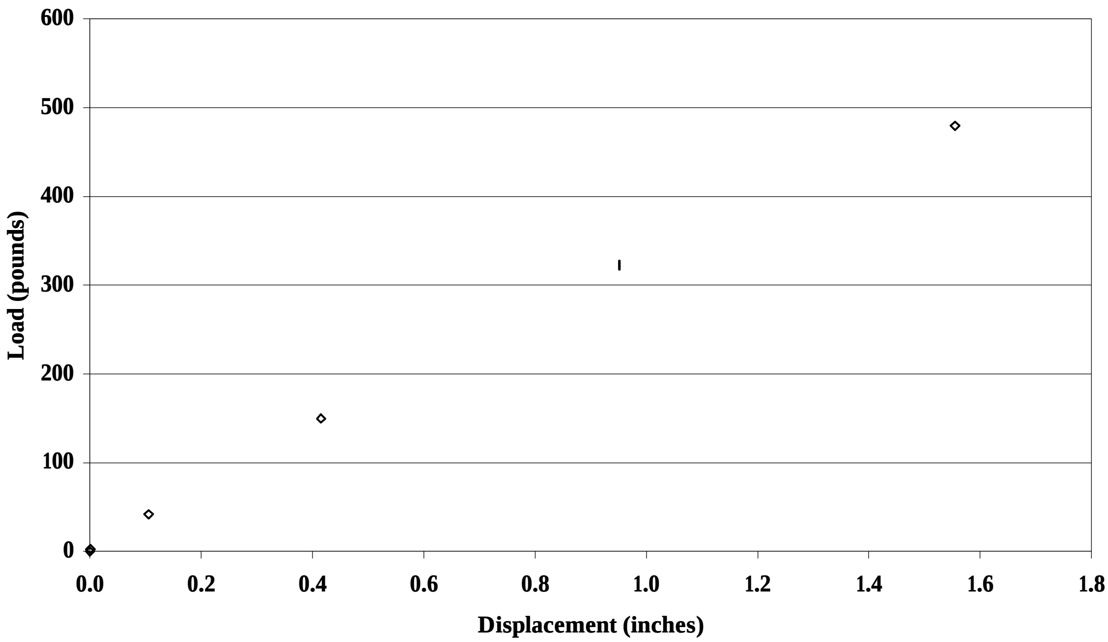

Load vs. Displacement at 18.0 in/min
HDPE 67.5 w/ MAPE # 36
Load (pounds)
600
500
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Displacement (inches)


Load vs. Displacement at 18.0 in/min
HDPE 67.5 w/ MAPE # 65
Load (pounds)
600
500
400
300
200
100
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Displacement (inches)

Load vs. Displacement at 18.0 in/min
HDPE 67.5 w/ MAPE # 66



Load vs. Displacement at 18.0 in/min
HDPE 67.5 w/ MAPE # 75



APPENDIX D

SHEAR-FREE DEFLECTION ANALYSIS

INTRODUCTION

As part of the load rate effects investigation, deflection was measured directly under the points of load application as well as at center span. The additional deflection readings allow an estimation of the true flexural modulus of the material to be made. The ratio of the true modulus (E_t) to the modulus calculated using the center span deflection, known as the apparent modulus (E_{app}), can be used to identify whether large shear deformations have occurred. The ratios were then compared to values obtained from Lockyear (1999) from tests performed on single and triple-box sections of PVC and HDPE 8. It was found that ratio values were similar.

MATERIALS AND METHODS

The materials used and procedures followed for testing can be found in Chapter Two. All modulus calculations were made using values within the "linear" range of data. Inspection of the data indicated a nearly linear stress-strain relationship over the range between 0% and 30% of the ultimate stress. The visual inspection was confirmed when a linear regression line was fit to the data in that range. R^2 values from the regression analysis were greater than 0.98 for all specimens tested.

The values for determining the ratio of E_t to E_{app} for comparison were found using the equation for 4-point bending including shear effects derived in Appendix B of Lockyear (1999). The values for E_t and the shear modulus (G) were taken from Tables 3-3 and 3-4 of Lockyear (1999), and section properties for the two-box cross-section were used.

RESULTS

Formulation	Ratio of E_t to E_{app}			
	4.6 mm/min	**62.5 mm/min**	**254 mm/min**	**457 mm/min**
PVC	0.96	0.97	1.02	1.10
HDPE 8	1.02	1.15	1.11	1.02
HDPE 67.5	1.00	1.21	1.08	0.97
HDPE 67.5 w/ MAPE	1.12	1.11	1.10	1.05

The values in the preceding table indicate that a rate-of-load effect may be present for some of the formulations, but a one-sided t test at the 0.05 significance level determined that there is not a statistical difference in ratio values over any interval of load rates, for any of the formulations.

The ratio values were compared to values calculated using data from tests conducted on single and triple-box sections of PVC and HDPE 8 by Lockyear (1999). Ratio values from the Lockyear data ranged between 1.00 and 1.02 for both formulations, which is in agreement with the results presented in the preceding table.
The following page contains the calculations performed and the range of values used.

From Lockyear:

HDPE: E ranged from 2929.4 to 3063.3 MPa
G ranged from 206.1 to 313.8 MPa for a single box
G ranged from 290.8 to 464.1 MPa for a triple box

PVC: E ranged from 6528.8 to 6550.0 MPa
G ranged from 700.6 to 1066.7 MPa for a single box
G ranged from 783.6 to 1250.0 MPa for a triple box

HDPE: E ranged from 424873.5 to 444294.1 psi
G ranged from 29892.3 to 45512.8 psi for a single box
G ranged from 42177.0 to 67312.0 psi for a triple box

PVC: E ranged from 946922.4 to 949997.2 psi
G ranged from 101613.4 to 154711.8 psi for a single box
G ranged from 113651.6 to 181297.2 psi for a triple box

HDPE: I = 2.597, A = 2.041 PVC: I = 2.636, A = 2.032

HDPE

$P := 300 \quad L := 72 \quad G := 54744.5 \quad E := 434583.8 \quad I := 2.597 \quad A := 2.041 \quad k := .708$

$$\Delta_B := \frac{23}{1296} \cdot \frac{P \cdot L^3}{E \cdot I} \quad \Delta_V := \frac{P \cdot L}{10 \cdot k \cdot G \cdot A} \quad \Delta_T := \Delta_B + \Delta_V \quad E_{app} := \frac{23}{1296} \cdot \frac{P \cdot L^3}{\Delta_T \cdot I} \quad Ratio := \frac{E}{E_{app}}$$

$\Delta_B = 1.761 \quad \Delta_V = 0.027 \quad \Delta_T = 1.788 \quad E_{app} = 427947.4 \quad Ratio = 1.016$

PVC

$P := 700 \quad L := 72 \quad G := 147474.4 \quad E := 948494.8 \quad I := 2.636 \quad A := 2.032 \quad k := .703$

$$\Delta_B := \frac{23}{1296} \cdot \frac{P \cdot L^3}{E \cdot I} \quad \Delta_V := \frac{P \cdot L}{10 \cdot k \cdot G \cdot A} \quad \Delta_T := \Delta_B + \Delta_V \quad E_{app} := \frac{23}{1296} \cdot \frac{P \cdot L^3}{\Delta_T \cdot I} \quad Ratio := \frac{E}{E_{app}}$$

$\Delta_B = 1.855 \quad \Delta_V = 0.024 \quad \Delta_T = 1.878 \quad E_{app} = 936414.8 \quad Ratio = 1.013$

REFERENCES

Lockyear, S. A. (1999). “Mechanical analysis of transversely loaded wood/plastic sections.” Masters thesis, Department of Civil and Environmental Engineering, Washington State University, Pullman, WA.

APPENDIX E

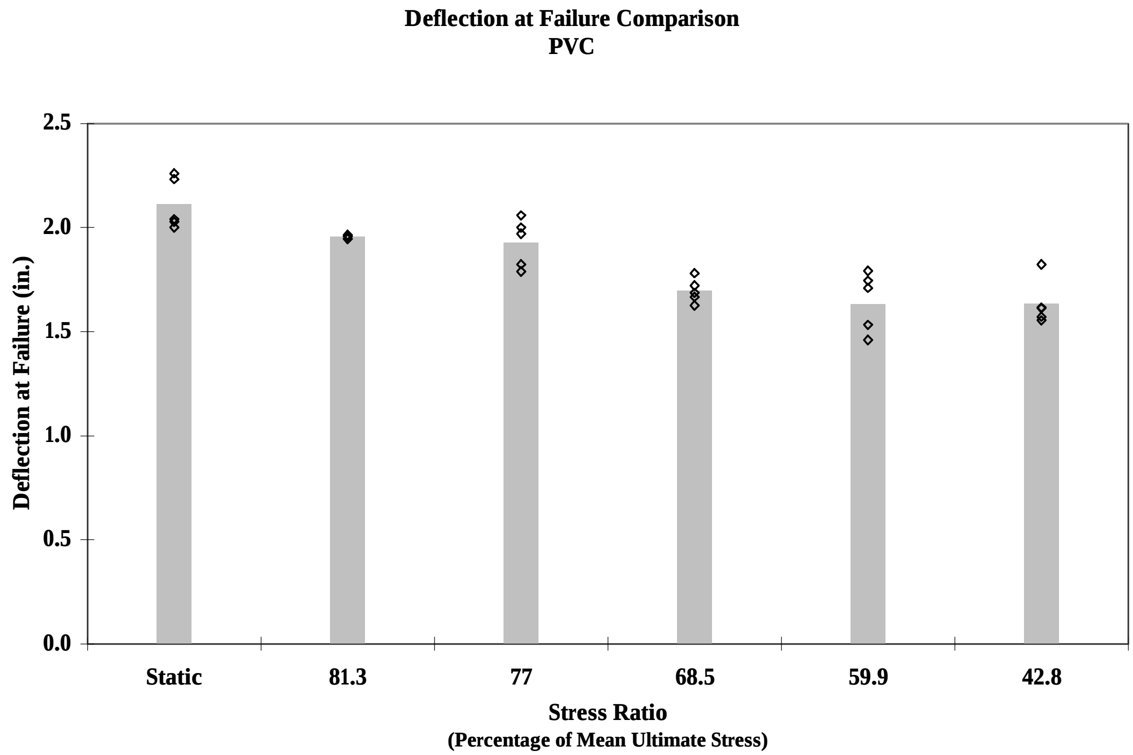
DEFLECTION AT FAILURE ANALYSIS

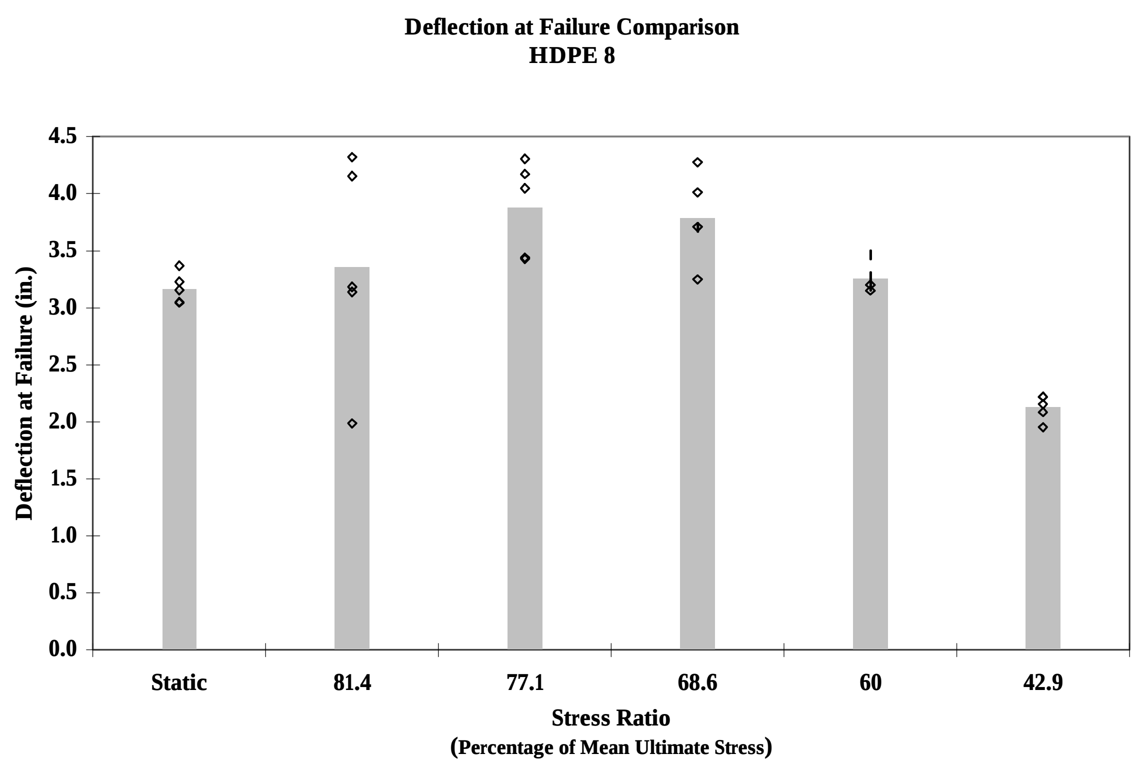
INTRODUCTION

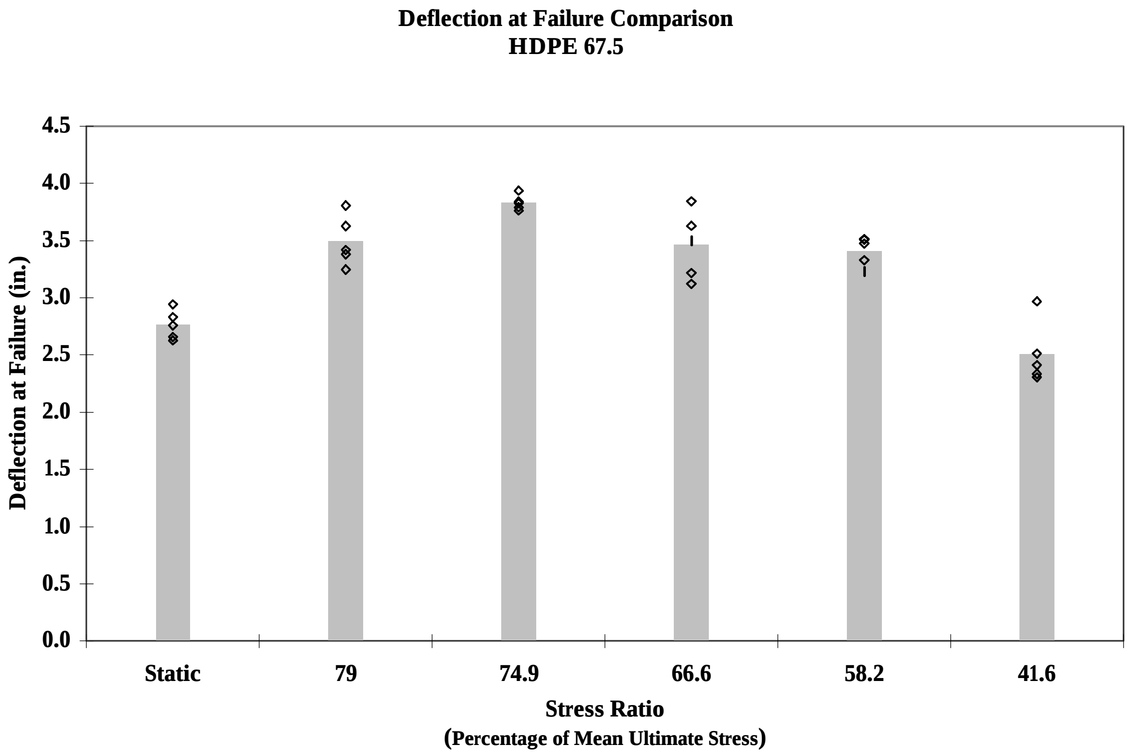
Deflection at failure measurements were recorded for both the load-duration and rate-of-load tests for the purpose of determining if failure is governed by a maximum strain value as presented in Lockyear (1999). Although strain was not measured directly or calculated with methods taking into account the neutral axis shift or the different tensile and compressive properties, deflection at failure can be used as an indicator of a strain-based failure mechanism. The deflection at failure values at different levels of applied stress, or at different rates of load application, were compared using an analysis of variance (ANOVA) for the duration-of-load results and with a one-sided t test at the 0.05 significance level for the rate-of-load results.

DURATION-OF-LOAD RESULTS

Deflection at failure data is presented as a bar chart. The bars represent the average deflection at failure and the individual points represent the recorded data points. At the highest stress level, some failures occurred during the upload stage of the test, thus these values are not plotted and were excluded from the analysis. At the lowest stress level, failures were observed only for the HPDE 67.5 w/ MAPE formulation during the 90-day test period. Consequently, the values for the lowest stress level are those measured at the end of the 90-day test period for all formulations except HDPE 67.5 w/ MAPE. Following the plots, the ANOVA results and data are presented in tabular form.


Deflection at Failure Comparison
PVC
Deflection at Failure (in.)
2.5
2.0
1.5
1.0
0.5
0.0
Static
81.3
77
68.5
59.9
42.8
Stress Ratio
(Percentage of Mean Ultimate Stress)


Deflection at Failure Comparison
HDPE 8
Deflection at Failure (in.)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Static
81.4
77.1
68.6
60
42.9
Stress Ratio
(Percentage of Mean Ultimate Stress)


Deflection at Failure Comparison
HDPE 67.5
Deflection at Failure (in.)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Static
79
74.9
66.6
58.2
41.6
Stress Ratio
(Percentage of Mean Ultimate Stress)

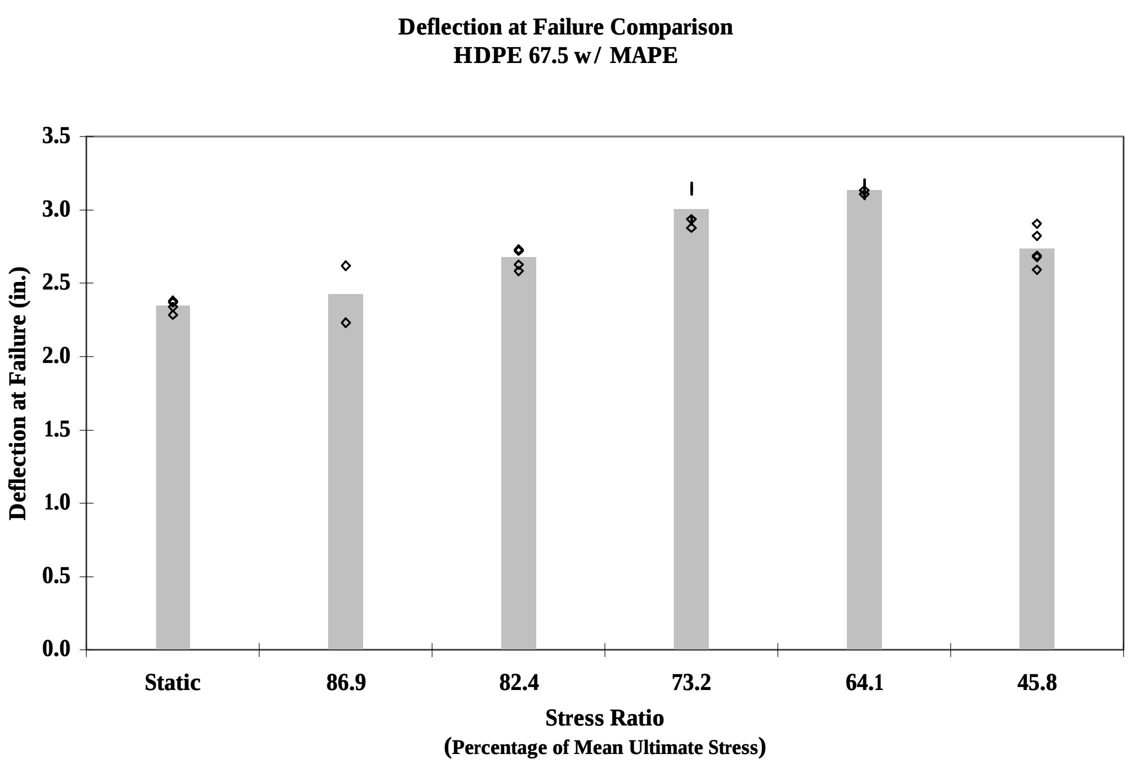

Deflection at Failure Comparison
HDPE 67.5 w/ MAPE
Deflection at Failure (in.)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Static
86.9
82.4
73.2
64.1
45.8
Stress Ratio
(Percentage of Mean Ultimate Stress)

Table E-1: *ANOVA Results for Deflection at Failure of PVC in Load-Duration Tests*

Property		Load Type		Load Type	ANOVA Result	
Δ_{fail}	at	Static	and	All DOL	ARE	Statistically Different
Δ_{fail}	at	Static	and	81.3%	ARE	Statistically Different
Δ_{fail}	at	Static	and	77.0%	ARE	Statistically Different
Δ_{fail}	at	Static	and	68.5%	ARE	Statistically Different
Δ_{fail}	at	Static	and	59.9%	ARE	Statistically Different
Δ_{fail}	at	Static	and	42.8%	ARE	Statistically Different
Δ_{fail}	at	81.3%	and	77.0%	ARE	Statistically Different
Δ_{fail}	at	81.3%	and	68.5%	ARE NOT	Statistically Different
Δ_{fail}	at	81.3%	and	59.9%	ARE NOT	Statistically Different
Δ_{fail}	at	81.3%	and	42.8%	ARE NOT	Statistically Different
Δ_{fail}	at	77.0%	and	68.5%	ARE	Statistically Different
Δ_{fail}	at	77.0%	and	59.9%	ARE	Statistically Different
Δ_{fail}	at	77.0%	and	42.8%	ARE	Statistically Different
Δ_{fail}	at	68.5%	and	59.9%	ARE NOT	Statistically Different
Δ_{fail}	at	68.5%	and	42.8%	ARE NOT	Statistically Different
Δ_{fail}	at	59.9%	and	42.8%	ARE NOT	Statistically Different

Table E-2: *ANOVA Data for Deflection at Failure of PVC in Load-Duration Tests*

Property	Load Type		Load Type	Within Sample Variation	Between Sample Variation	F value	F_α (α=.05)	F > F_α ?
Δ_{fail}	Static	to	All DOL	0.0242	0.9485	39.24	4.226	YES
Δ_{fail}	Static	to	81.3%	0.2156	2.0311	9.42	5.99	YES
Δ_{fail}	Static	to	77.0%	0.0144	0.0844	5.85	5.32	YES
Δ_{fail}	Static	to	68.5%	0.0093	0.4339	46.49	5.32	YES
Δ_{fail}	Static	to	59.9%	0.0180	0.5393	29.98	5.32	YES
Δ_{fail}	Static	to	42.8%	0.0134	0.5691	42.45	5.32	YES
Δ_{fail}	81.3%	to	77.0%	0.2148	1.2875	5.99	5.99	YES
Δ_{fail}	81.3%	to	68.5%	0.2097	0.5875	2.80	5.99	NO
Δ_{fail}	81.3%	to	59.9%	0.2184	0.4772	2.19	5.99	NO
Δ_{fail}	81.3%	to	42.8%	0.2138	0.4500	2.10	5.99	NO
Δ_{fail}	77.0%	to	68.5%	0.0085	0.1356	15.88	5.32	YES
Δ_{fail}	77.0%	to	59.9%	0.0172	0.1970	11.46	5.32	YES
Δ_{fail}	77.0%	to	42.8%	0.0126	0.2152	17.07	5.32	YES
Δ_{fail}	68.5%	to	59.9%	0.0121	0.0057	0.47	5.32	NO
Δ_{fail}	68.5%	to	42.8%	0.0075	0.0092	1.22	5.32	NO
Δ_{fail}	59.9%	to	42.8%	0.0162	0.0004	0.02	5.32	NO

The ANOVA results show that PVC deflection at failure values were not constant over all intervals tested, and that the static results were not similar to the duration-of-load (DOL) results. Over the lower three stress levels, deflections were statistically similar. It should be noted that the 42.8% stress level did not produce any failures after 90 days, so the values used were the 90-day deflections.

Table E-3: *ANOVA Results for Deflection at Failure of HDPE 8 in Load-Duration Tests*

Property		Load Type		Load Type	ANOVA Result	
Δ_{fail}	at	Static	and	All DOL	ARE	Statistically Different
Δ_{fail}	at	Static	and	81.4%	ARE NOT	Statistically Different
Δ_{fail}	at	Static	and	77.1%	ARE	Statistically Different
Δ_{fail}	at	Static	and	68.6%	ARE	Statistically Different
Δ_{fail}	at	Static	and	60.0%	ARE	Statistically Different
Δ_{fail}	at	Static	and	42.9%	ARE	Statistically Different
Δ_{fail}	at	81.4%	and	77.1%	ARE NOT	Statistically Different
Δ_{fail}	at	81.4%	and	68.6%	ARE NOT	Statistically Different
Δ_{fail}	at	81.4%	and	60.0%	ARE NOT	Statistically Different
Δ_{fail}	at	81.4%	and	42.9%	ARE	Statistically Different
Δ_{fail}	at	77.1%	and	68.6%	ARE NOT	Statistically Different
Δ_{fail}	at	77.1%	and	60.0%	ARE	Statistically Different
Δ_{fail}	at	77.1%	and	42.9%	ARE	Statistically Different
Δ_{fail}	at	68.6%	and	60.0%	ARE	Statistically Different
Δ_{fail}	at	68.6%	and	42.9%	ARE	Statistically Different
Δ_{fail}	at	60.0%	and	42.9%	ARE	Statistically Different

Table E-4: *ANOVA Data for Deflection at Failure of HDPE 8 in Load-Duration Tests*

Property	Load Type		Load Type	Within Sample Variation	Between Sample Variation	F value	F_α (α=.05)	$F > F_\alpha$?
Δ_{fail}	Static	to	All DOL	0.5318	2.8520	5.36	4.198	YES
Δ_{fail}	Static	to	81.4%	0.4645	1.1955	2.57	5.32	NO
Δ_{fail}	Static	to	77.1%	0.1120	3.6835	32.88	5.32	YES
Δ_{fail}	Static	to	68.6%	0.0991	3.1650	31.95	5.32	YES
Δ_{fail}	Static	to	60.0%	0.0330	0.8735	26.49	5.32	YES
Δ_{fail}	Static	to	42.9%	0.0314	0.7245	23.10	5.32	YES
Δ_{fail}	81.4%	to	77.1%	0.5261	0.6821	1.30	5.32	NO
Δ_{fail}	81.4%	to	68.6%	0.5132	0.4701	0.92	5.32	NO
Δ_{fail}	81.4%	to	60.0%	0.4471	0.0252	0.06	5.32	NO
Δ_{fail}	81.4%	to	42.9%	0.4455	3.7813	8.49	5.32	YES
Δ_{fail}	77.1%	to	68.6%	0.1607	0.0197	0.12	5.32	NO
Δ_{fail}	77.1%	to	60.0%	0.0946	0.9695	10.24	5.32	YES
Δ_{fail}	77.1%	to	42.9%	0.0930	7.6752	82.51	5.32	YES
Δ_{fail}	68.6%	to	60.0%	0.0817	0.7131	8.73	5.32	YES
Δ_{fail}	68.6%	to	42.9%	0.0801	6.9180	86.41	5.32	YES
Δ_{fail}	60.0%	to	42.9%	0.0140	3.1890	228.22	5.32	YES

The ANOVA results show that HDPE 8 deflection at failure values were not constant over all intervals tested, and that the static results were not similar to the duration-of-load (DOL) results. Over the first three stress levels, deflections were statistically similar, but as the stress level decreased over the final two stress levels the similarity vanished. It should be noted that the 42.9% stress level did not produce any failures after 90 days, so the values used were the 90-day deflections.

Table E-5: *ANOVA Results for Deflection at Failure of HDPE 67.5 in Load-Duration Tests*

Property		Load Type		Load Type	ANOVA Result	
Δ_{fail}	at	Static	and	All DOL	ARE	Statistically Different
Δ_{fail}	at	Static	and	79.0%	ARE	Statistically Different
Δ_{fail}	at	Static	and	74.9%	ARE	Statistically Different
Δ_{fail}	at	Static	and	66.6%	ARE	Statistically Different
Δ_{fail}	at	Static	and	58.2%	ARE	Statistically Different
Δ_{fail}	at	Static	and	41.6%	ARE NOT	Statistically Different
Δ_{fail}	at	79.0%	and	74.9%	ARE	Statistically Different
Δ_{fail}	at	79.0%	and	66.6%	ARE NOT	Statistically Different
Δ_{fail}	at	79.0%	and	58.2%	ARE NOT	Statistically Different
Δ_{fail}	at	79.0%	and	41.6%	ARE	Statistically Different
Δ_{fail}	at	74.9%	and	66.6%	ARE	Statistically Different
Δ_{fail}	at	74.9%	and	58.2%	ARE	Statistically Different
Δ_{fail}	at	74.9%	and	41.6%	ARE	Statistically Different
Δ_{fail}	at	66.6%	and	58.2%	ARE NOT	Statistically Different
Δ_{fail}	at	66.6%	and	41.6%	ARE	Statistically Different
Δ_{fail}	at	58.2%	and	41.6%	ARE	Statistically Different

Table E-6: *ANOVA Data for Deflection at Failure of HDPE 67.5 in Load-Duration Tests*

Property	Load Type		Load Type	Within Sample Variation	Between Sample Variation	F value	F_α (α=.05)	$F > F_\alpha$?
Δ_{fail}	Static	to	All DOL	0.2104	2.5017	11.89	4.198	YES
Δ_{fail}	Static	to	79.0%	0.0327	1.3395	40.91	5.32	YES
Δ_{fail}	Static	to	74.9%	0.0105	2.8535	271.58	5.32	YES
Δ_{fail}	Static	to	66.6%	0.0521	1.2178	23.39	5.32	YES
Δ_{fail}	Static	to	58.2%	0.0163	1.0462	64.35	5.32	YES
Δ_{fail}	Static	to	41.6%	0.0447	0.1656	3.70	5.32	NO
Δ_{fail}	79.0%	to	74.9%	0.0267	0.2829	10.61	5.32	YES
Δ_{fail}	79.0%	to	66.6%	0.0682	0.0029	0.04	5.32	NO
Δ_{fail}	79.0%	to	58.2%	0.0324	0.0181	0.56	5.32	NO
Δ_{fail}	79.0%	to	41.6%	0.0609	2.4471	40.18	5.32	YES
Δ_{fail}	74.9%	to	66.6%	0.0460	0.3431	7.46	5.32	YES
Δ_{fail}	74.9%	to	58.2%	0.0102	0.4441	43.65	5.32	YES
Δ_{fail}	74.9%	to	41.6%	0.0387	4.3942	113.65	5.32	YES
Δ_{fail}	66.6%	to	58.2%	0.0517	0.0065	0.13	5.32	NO
Δ_{fail}	66.6%	to	41.6%	0.0802	2.2816	28.44	5.32	YES
Δ_{fail}	58.2%	to	41.6%	0.0444	2.0444	46.03	5.32	YES

The ANOVA results show that HDPE 67.5 deflection at failure values were not constant over all intervals tested, and that the static results were not similar to the duration-of-load (DOL) results. With the exception of the 74.9% stress level, deflections were statistically similar for the ratios that produced failures. It should be noted that the 42.9% stress level did not produce any failures after 90 days, so the values used were the 90-day deflections.

Table E-7: *ANOVA Results for Deflection at Failure of HDPE 67.5 w/ MAPE in Load-Duration Tests*

Property		Load Type		Load Type	ANOVA Result	
Δ_{fail}	at	Static	and	All DOL	ARE	Statistically Different
Δ_{fail}	at	Static	and	86.9%	ARE	Statistically Different
Δ_{fail}	at	Static	and	82.4%	ARE	Statistically Different
Δ_{fail}	at	Static	and	73.2%	ARE	Statistically Different
Δ_{fail}	at	Static	and	64.1%	ARE	Statistically Different
Δ_{fail}	at	Static	and	45.8%	ARE	Statistically Different
Δ_{fail}	at	86.9%	and	82.4%	ARE	Statistically Different
Δ_{fail}	at	86.9%	and	73.2%	ARE	Statistically Different
Δ_{fail}	at	86.9%	and	64.1%	ARE	Statistically Different
Δ_{fail}	at	86.9%	and	45.8%	ARE	Statistically Different
Δ_{fail}	at	82.4%	and	73.2%	ARE	Statistically Different
Δ_{fail}	at	82.4%	and	64.1%	ARE	Statistically Different
Δ_{fail}	at	82.4%	and	45.8%	ARE NOT	Statistically Different
Δ_{fail}	at	73.2%	and	64.1%	ARE NOT	Statistically Different
Δ_{fail}	at	73.2%	and	45.8%	ARE	Statistically Different
Δ_{fail}	at	64.1%	and	45.8%	ARE	Statistically Different

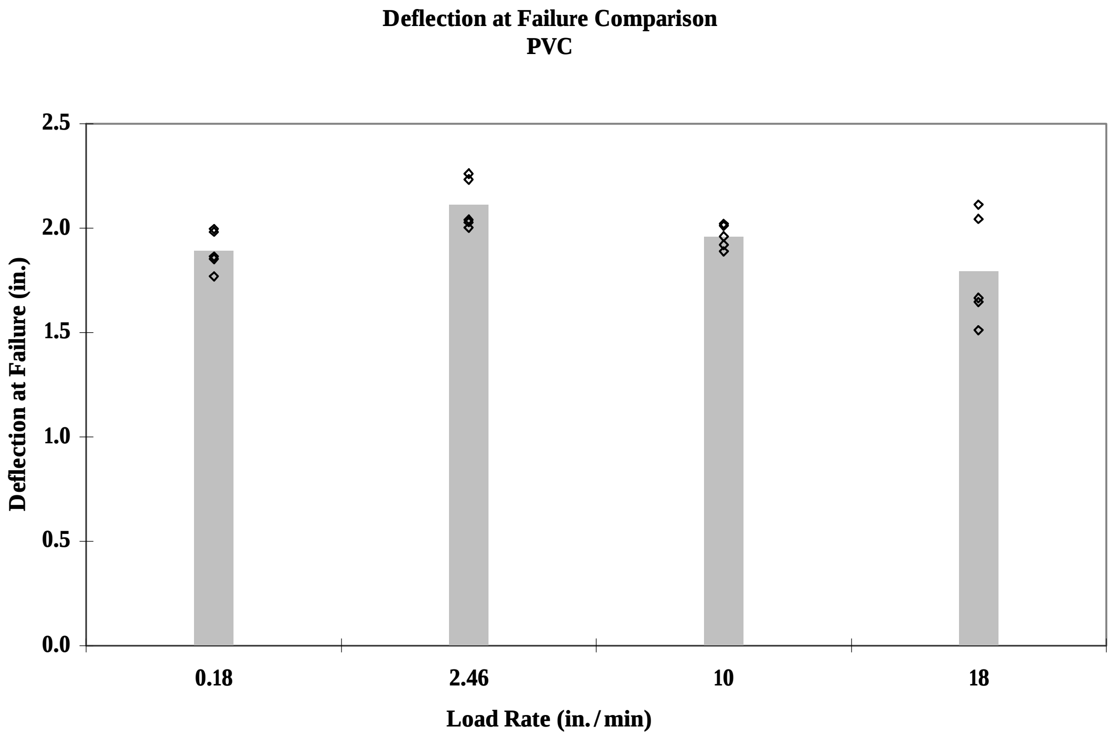
Table E-8: *ANOVA Data for Deflection at Failure of HDPE 67.5w/ MAPE in Load-Duration Tests*

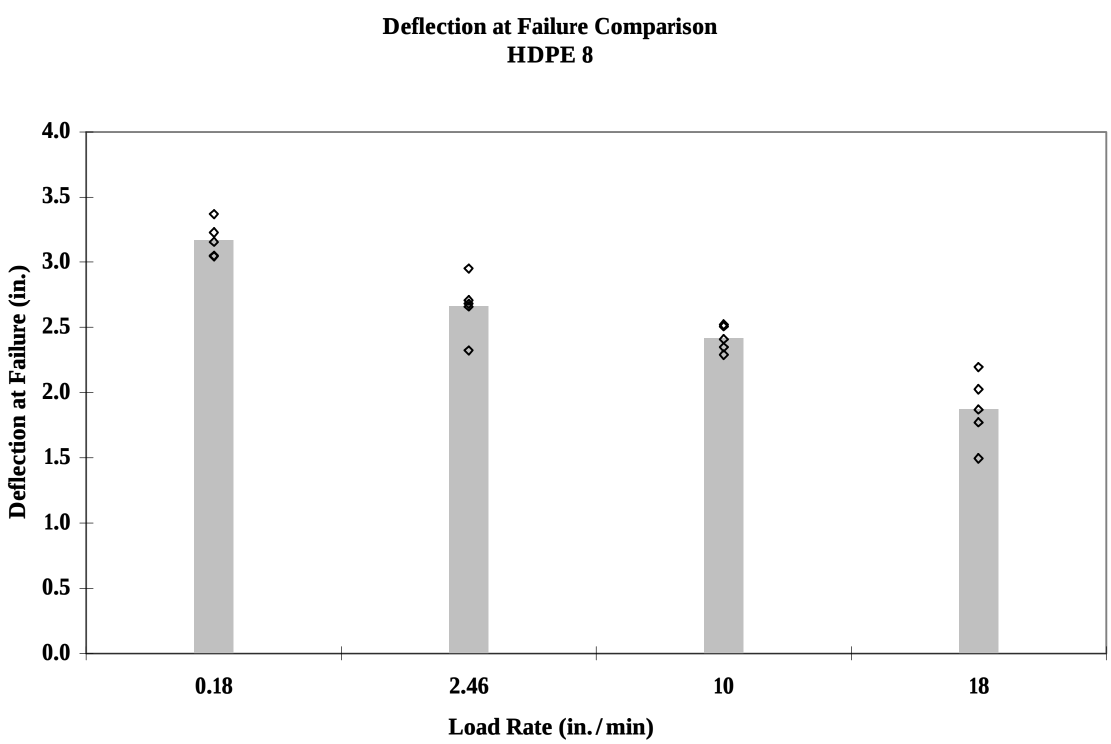
Property	Load Type		Load Type	Within Sample Variation	Between Sample Variation	F value	F_α (α=.05)	$F > F_\alpha$?
Δ_{fail}	Static	to	All DOL	0.0475	1.8631	39.19	4.24	YES
Δ_{fail}	Static	to	86.9%	0.2890	2.4001	8.30	6.61	YES
Δ_{fail}	Static	to	82.4%	0.0031	0.2715	88.14	5.32	YES
Δ_{fail}	Static	to	73.2%	0.0090	1.0835	120.72	5.32	YES
Δ_{fail}	Static	to	64.1%	0.0012	1.5424	1254.29	5.32	YES
Δ_{fail}	Static	to	45.8%	0.0087	0.3787	43.64	5.32	YES
Δ_{fail}	86.9%	to	82.4%	0.2906	4.2859	14.75	6.61	YES
Δ_{fail}	86.9%	to	73.2%	0.2965	6.7088	22.63	6.61	YES
Δ_{fail}	86.9%	to	64.1%	0.2887	7.7906	26.98	6.61	YES
Δ_{fail}	86.9%	to	45.8%	0.2962	4.6854	15.82	6.61	YES
Δ_{fail}	82.4%	to	73.2%	0.0105	0.2703	25.66	5.32	YES
Δ_{fail}	82.4%	to	64.1%	0.0028	0.5197	186.30	5.32	YES
Δ_{fail}	82.4%	to	45.8%	0.0102	0.0089	0.87	5.32	NO
Δ_{fail}	73.2%	to	64.1%	0.0087	0.0404	4.65	5.32	NO
Δ_{fail}	73.2%	to	45.8%	0.0161	0.1811	11.23	5.32	YES
Δ_{fail}	64.1%	to	45.8%	0.0084	0.3926	46.81	5.32	YES

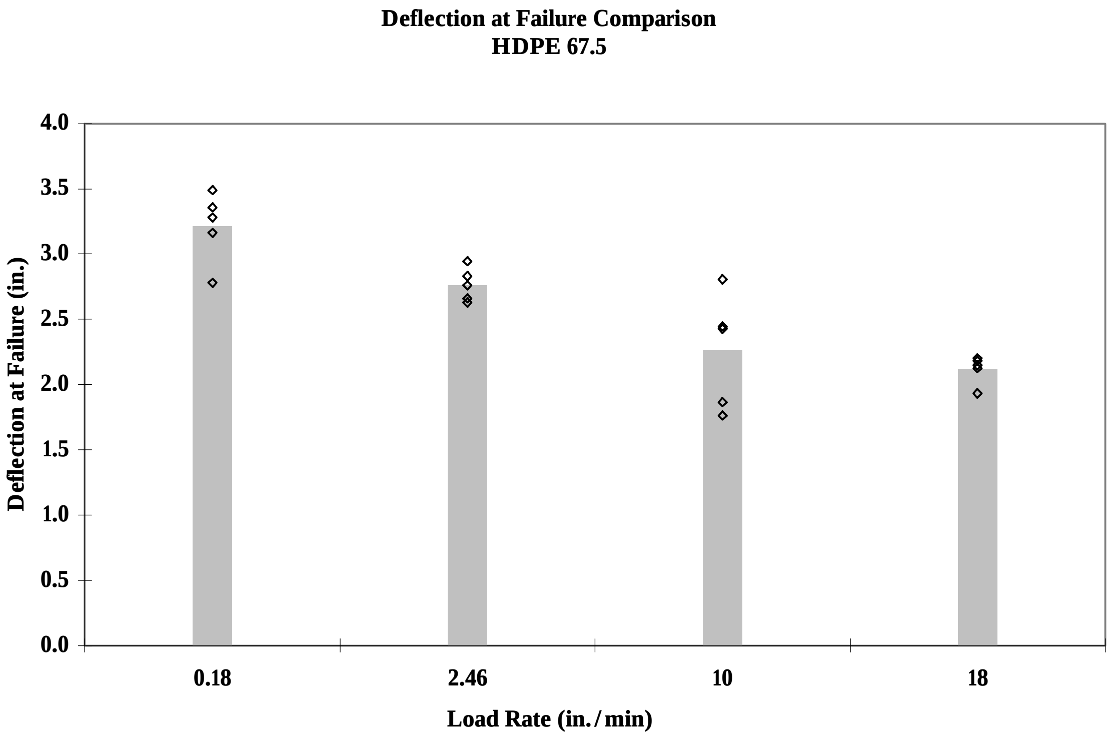
The ANOVA results show that HDPE 67.5 w/ MAPE deflection at failure values were not constant over all intervals tested, and that the static results were not similar to the duration-of-load (DOL) results. With the exception of two stress level intervals, deflections were statistically different for all ratios tested. It should be noted that the 45.8% stress level produced failures in all five specimen tested prior to the 90-day test limit.

LOAD RATE RESULTS

Deflection at failure data is presented as a bar chart (in US customary units). The bars represent the average deflection at failure and the individual points represent the recorded data points. Following the plots, the t test results are presented in tabular form.


Deflection at Failure Comparison
PVC
Deflection at Failure (in.)
2.5
2.0
1.5
1.0
0.5
0.0
0.18
2.46
10
18
Load Rate (in./min)


Deflection at Failure Comparison
HDPE 8
Deflection at Failure (in.)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.18
2.46
10
18
Load Rate (in./min)


Deflection at Failure Comparison
HDPE 67.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Deflection at Failure (in.)
0.18
2.46
10
18
Load Rate (in./min)

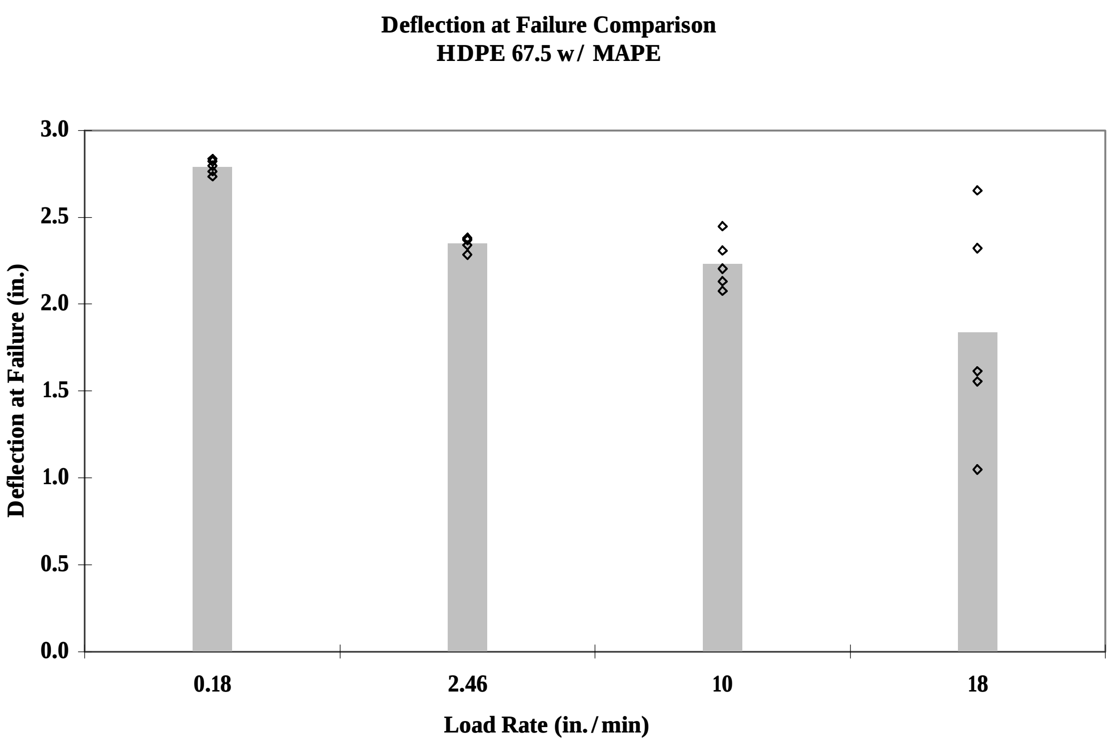

Deflection at Failure Comparison
HDPE 67.5 w/ MAPE
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Deflection at Failure (in.)
0.18
2.46
10
18
Load Rate (in./min)

Table E-9: *t Test Results for Deflection at Failure*

Formulation	T Statistic	T Critical	P-Value
PVC			
4.6 mm/min to 62.5 mm/min	3.103	1.860	0.007
62.5 mm/min to 254 mm/min	2.347	1.860	0.023
HDPE 8			
4.6 mm/min to 62.5 mm/min	3.749	1.860	0.003
62.5 mm/min to 254 mm/min	1.154	1.860	0.141
HDPE 67.5			
4.6 mm/min to 62.5 mm/min	2.873	1.860	0.010
62.5 mm/min to 254 mm/min	3.203	1.860	0.006

The results show that deflection at failure values changed with the increase in rate-of-load application for all formulations over all intervals with the exception of HDPE 8 over the 62.5 mm/min to 254 mm/min interval.