

Engineering Properties
of Wood-Plastic Composite Panels

by

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Abstract

Over the past decade, there has been a growing interest in the development of consumer and industrial products composed of wood fillers combined with thermoplastic resins. The use of wood flour as a reinforcing filler for thermoplastics has several benefits. Wood fillers have the advantage of being renewable, inexpensive, lightweight, and non-abrasive to processing equipment. Both materials can be obtained from post-consumer or post-industrial recycling sources.

Little information is available concerning the engineering characteristics of wood-plastic composite panels. Recently, there has been an increasing interest in using this type of material for a variety of structural applications. To quantify the material performance, several different wood-flour thermoplastic formulations ranging from 0% to 60% wood filler content by weight were produced and tested according to the ASTM D1037 standard for wood-based panels. A matched set of specimens underwent the accelerated aging process outlined in the standard. It was found that by increasing the ratio of wood filler, the material performance properties were altered. The modulus of elasticity and water absorption increased, while the coefficient of thermal expansion and ultimate stress values decreased. The aging process had very little effect on the 0% wood filler content samples and decreased the material performance in some properties for the higher wood percentage panels.

The results were compared with conventional wood-based panel products. Included were particleboard, hardboard, plywood, medium density fiberboard, and oriented strandboard. Though the stiffness of wood-plastic composite panels were generally less than conventional wood-based products, many other material properties were similar.

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Chapter 1 – Introduction

Concerns have risen for decreasing the quantity of waste sent to landfills highlighting the importance of recycling. Recent municipal waste statistics indicate the potential for increasing the recycling market. Both wood and plastic are major components of the waste stream. The global use of plastics has increased by 194 percent from 1974 to 1994 contributing to an annual 18.7 million tons currently sent to landfills (Bowyer 1997, EPA 1997). Out of this enormous quantity of discarded plastic, only 4 percent is recovered (Krishnaswamy, 1997). Wood is another prevalent material commonly discarded totaling up to 69 million metric tons annually in the United States (Ince, 1995). In efforts to reduce sending waste to landfills, new products are being developed to utilize recycled materials.

Wood-filled composites are currently being developed for use as building products that utilize post-consumer and post-industrial wood and plastic waste. Plastic lumber, a lumber substitute product manufactured largely from waste plastic, has started to impact the plastic recycling market and continues to grow. These types of products can potentially consume large amounts of waste material.

While the use of waste materials is appealing, the availability of recycled material alone is not enough to create new markets. Plastic has advantages over other materials currently used in the building industry. One of the greatest advantages of plastic is that it is not effected by moisture and therefore will not decay. It also is not susceptible to insect infestation or corrosion and can be molded into many shapes.

A major limitation for using thermoplastic in building applications is that many unreinforced plastic resins have low stiffness relative to conventional wood products. Compounding wood flour with plastic is intended to increase the modulus of elasticity of

the plastic resin and therefore make it more usable for structural applications.

1.1 Motivation for Research

The use of wood filled plastics as a building material or structural member has great potential. However, information is lacking on the engineering properties of these products. If these engineered materials are going to be used, their properties must be quantified. Engineering data on wood fiber-plastic composites is limited, inconclusive, or proprietary in nature. In addition to the current uncertainties associated with the composite material, there are questions on how different quantities of wood flour filler will effect the structural performance of the products.

1.2 Hypothesis and Objectives

The following hypotheses were pursued in this thesis with the corresponding objectives.

1. Wood flour used as a filler in thermoplastics provides certain benefits to the material properties.

Values will be obtained for mechanical and physical properties (e.g., bending modulus of elasticity (MOE), thermal expansion, etc.) from tests of specimens with various wood flour/thermoplastic ratios by weight. A comparison will be made between the different formulations of wood flour and thermoplastic. Relationships between wood and thermoplastic content will be defined for each material property. When practical, an equation will be used to describe the trend and statistical analysis will be performed for the tests considered being primary in importance.

2. Wood-plastic composite panels have advantages over conventional wood-based panel products for some applications.

The objective is to identify the material properties where using wood-plastic composite panels would be advantageous over conventional wood products.

Primary test results from past studies of conventional wood products will be reviewed. These values will be compared with the data from this study to create a better understanding of the material properties of wood-plastic composites relative to familiar wood-based products.

1.3 Scope

In order to quantify the reinforcing effect of adding wood flour to plastic, six different formulations were investigated ranging from 0 to 60 by weight. The 0% wood flour was the control group for the evaluation process. The manufactured panels were all one-half inch thick and were cut to the required ASTM testing dimensions.

Ten different tests were performed in order to quantify the engineering properties of the wood-plastic composite material. All tests followed the ASTM D1037-91 Standard intended for evaluating wood-based panels. The tests were divided into two categories; primary and secondary. Tests considered to be essential for common applications were assigned to the primary category. This was often determined by the available material properties of conventional wood-based panels. Data from the remaining tests are considered as secondary, used to contribute to a more complete evaluation of wood-plastic composite panels. Primary tests are denoted in Chapter 5 within their corresponding subsections. Statistical analysis was performed to compare mean values of the primary tests.

The specimens were conditioned at standard humidity and temperature, 65% relative humidity and 74°F (23°C), unless otherwise dictated by the testing standard. The material tests are listed and described in Chapter 4. Unless noted otherwise, ten specimens were tested for each variable under consideration. Preliminary results were obtained from three to five samples. Greater accuracy could be found in the mean values by increasing the number of samples. But, limitations in production did not allow for a large number of specimens for the proposed number of tests.

The project also quantified the effects of aging on the panels. Durability against weather exposure is critical for wood-plastic composites since they are often used in outdoor environments with high humidity levels. The tests described above were repeated for a matched set of specimens after they had been subjected to the accelerated aging process. This allowed for a direct comparison of engineering properties for aged and unaged specimens.

Chapter 2 – Background

2.1 General Information on Plastics

In general, there are two basic types of plastics: thermosets and thermoplastics. One main distinction separates the two type of plastics. A thermoset undergoes an internal chemical process during the solidification of the initial set. This process locks the molecules together forming a network that can not be broken by reheating the material. In contrast, a thermoplastic can easily be melted, shaped, and cooled to a new form while retaining its original properties. This is attributed to the molecule's ability to slide freely past one another when they are reheated above the melting temperature allowing a product to be molded into different shapes. The ability to be reshaped along with the availability of thermoplastics in the waste stream make it an ideal candidate for recycling.

Thermoplastic resins are widely used in the United States, with an annual production as high as 69.5 billion pounds (SPI, 1997). These plastics account for approximately 78 percent of the plastic market production as shown in Figure 2.1 on the following page. A large portion of thermoplastics is used for packaging. Considering that packaging is used as a temporary product, it is commonly discarded forming a large amount of material available for recycling. While this study focuses on using recycled thermoplastic, virgin resins or a mix of virgin and recycled resins can also be used in producing wood-plastic composite panels.

Recycled thermoplastics are available from both post-consumer and post-industrial sources. Generally, post-industrial sources are more homogeneous and cleaner because they originate from a controlled environment. Post-consumer products have the potential to be accepted as a viable recycling source and large quantities are currently available, often at

a low cost. Although not as easy to use as other sources because of contamination, they can still be processed similar to post-industrial and virgin resins. It has been shown that panels made with recycled plastic compare favorably with those consisting of virgin resins (Youngquist, 1994).

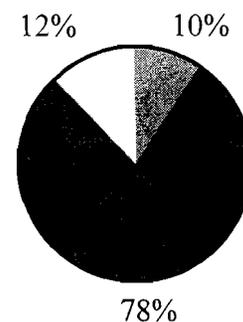
2.2 Thermoplastic Resins

Six types of thermoplastic resins dominate the plastic market, as shown in Table 2.1. These include: low density polyethylene (LDPE), linear low density polyethylene (LLDPE), high density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC).

Table 2.1 – 1997 U.S. Production of Thermoplastics by Resin

Resin	Millions of Pounds	Percentage Produced
LDPE	7,691	11
LLDPE	6,888	10
HDPE	12,557	18
PP	13,320	19
PS	6,380	9
PVC	14,084	20
Thermoplastic Polyester	4,260	6
Other	4,315	6
Total	69,495	100

■ Thermoset ■ Thermoplastic □ Other



From: Society of the Plastics Industry, 1997 Year End Statistics

Figure 2.1 - Types of Plastics Based on 1997 U.S. Production

Each type of resin possesses a distinct molecular composition and structure. The differences give each resin a unique set of mechanical properties. Depending on the resin, properties can vary twice that of another polymer.

Selecting the proper resin depends on the processing used in manufacturing, the predicted end use of the product, and cost. In addition to the resins available, many types

can be compounded to form plastics with a new set of properties (e.g., melt flow index, molecular weight). Selecting the proper resin can be quite difficult considering the many variables that need to be considered.

2.3 Fillers

Fillers are commonly used in thermoplastics to decrease cost and enhance performance. Several billion pounds of fillers are used annually in composite products (Sanadi, 1995). Minerals such as talc and calcium carbonate are common fillers, although higher performance applications use glass or synthetic fibers. Over the past two decades, many different natural fibers have been combined with thermoplastic resins to produce new composite blends. These include agricultural fibers (e.g., wheat, kenaf, sisal, etc.) and waste wood (e.g., wood flour, old newspaper, etc.). Wood flour originates from sawdust ground and screened usually finer than individual wood fibers.

It has been shown that the engineering properties of composites filled with natural fibers are higher than some composites using traditional fillers (Jacobson, 1995). Currently there is an abundance of waste fiber products available for recycling that can be used in fiber-plastic composites. English and Falk have made investigations on the effects of adding wood fillers to plastic (1995). They concluded that these natural fiber fillers have several advantages over mineral and glass fiber fillers. Wood fiber fillers are lighter in weight and possess a specific gravity about half of mineral and glass fillers. Another advantage is that natural fibers are less abrasive on processing equipment than mineral or glass fibers. Adding wood fibers to plastic significantly increases stiffness. Also, adding wood fibers to plastic greatly reduces the thermal expansion of the plastic. The use of wood flour as a filler in the thermoplastics market is continually increasing (Berger, 1997).

2.4 Processing Issues

There are many methods and options for processing thermoplastics. A previous study concluded that the material properties of thermoplastic products can vary up to 230 percent by manufacturer (Lampo, 1997). This was attributed to variations in processing and the feedstock content. Another study concluded that composite properties are greatly influenced by the processing technique as well as the production method (Pereira, 1997). These conclusions emphasize the importance of how processing influences variation in material properties. It is imperative to have an understanding of the processing methods and issues when specifying plastic resins. Different compounding and forming methods require certain material characteristics in order to operate successfully.

Wood-plastic composites maintain their original material properties after numerous processing cycles (Myers, 1993). This indicates that the composite material can be recycled without significant property losses. Manufacturing waste along with discarded consumer products can be recycled preventing them from entering landfills.

Using wood fillers over traditional materials presents new challenges. Plastic processing does not tolerate moisture during heating cycles. Wood retains moisture that can cause complications during the compounding process. When wet wood is heated with the base material, steam can form creating voids in the product. To alleviate this problem, the wood flour must be thoroughly dried prior to processing. Another issue associated with wood fiber is that it is combustible. Melt temperatures must be kept below the ignition temperature of wood. Therefore, plastics with a high melt temperature are not suited for wood fiber compounding applications. Generally, processing temperatures must be kept below or near 392°F (200°C) to avoid degradation of the wood fiber.

2.4.1 Pelletized Feedstock

For consistency in material handling, the thermoplastic forming industry typically uses plastic pellets as feedstock, as seen in Figure 2.2, for material processing units. These

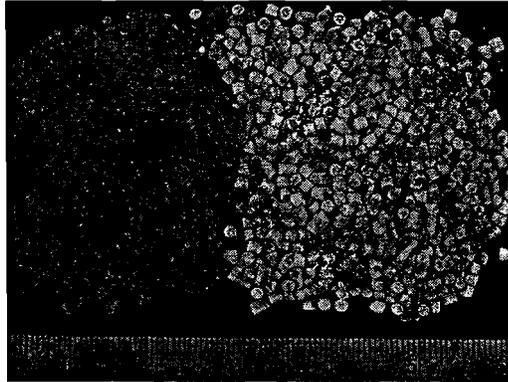


Figure 2.2 – Pelletized Feedstock Commonly Used in Plastic Manufacturing

pellets are usually about 1/8-inch in diameter and often contain the desired type of resin and color as the finished product. One of the major benefits of using pelletized feedstock is its versatility for processing equipment. For example, a pellet supplier can sell the same feedstock to a car manufacturer for molded door panels and to a window factory for extruding plastic jambs. Using this philosophy, pellet compounders blend thermoplastic and wood filler into a comparable pellet form. Another benefit of using pellets is to reduce the dust levels in product manufacturing. Dust collection systems are only needed before the mixing process because the pellet encapsulates all of the fibers.

Using the same bulk material form easily allows manufactures to switch from a one hundred percent plastic feedstock to a wood-plastic blend without making major processing changes. This makes wood-plastic composite material much more marketable since a manufacturer can switch materials without making a large capital investment. Any cost in

changing materials would be associated with temporarily stopping production lines to change the feed material.

2.4.2 Compounding

Researchers have tried several blending methods to evenly distribute the wood flour through the resin without thermally degrading the material (English, 1995). Many compounding machines have been evaluated such as single screw extruders, kneaders, thermokinetic mixers, and twin screw extruders. Each machine has control variables, that when adjusted, modify the quality of the final product. Additives such as coupling agents and dyes can be introduced during the compounding process to enhance the final product.

The single screw extruder dates back to 1935 and was designed specifically for mixing thermoplastics (Rauwendaal, 1990). Its main functions include, compacting the feedstock, melting the feedstock, pumping and mixing the melted plastic and additives, and finally, extruding the mix. The machine is arranged in a linear configuration with the hopper at the beginning of the barrel. A screw is housed inside of the barrel that forces the feedstock through the machine. There are different regions along the screw performing the various functions previously described. The screw can be modified to adapt for greater amounts of mixing or barrel velocities. One common modification for increasing mixing for thermoplastics involves adding pins to the barrel in the mixing region to split the flow.

Many types of kneaders have been used for mixing and processing since the late 19th century (Osswald, 1996). The Buss kneader has been evaluated for compounding wood flour and thermoplastics. Technically, a kneader is a single screw machine, but the screw's reciprocating motion distinguishes it from typical screw mixers. The addition of the reciprocating motion of the screw wipes the barrel and pins on each revolution. This

interaction enhances the distribution of additives throughout the base resin. The Buss kneader has several other benefits. The modular barrel and screw allow for changes in length giving compounding flexibility. A vapor removal system efficiently removes gases and therefore fiber predrying is not required. These features make the Buss kneader a suitable machine for wood-plastic composite compounding (Stropoli, 1997).

The thermokinetic, or K-mixer, uses intense shear forces to fiberize fillers with rotating blades. This machine also evaporates water and melts the polymer mixing it with the additives. Mixing is terminated when the material reaches a preset temperature. Problems have been associated with attempting to feed lightweight fiber materials into the mixing chamber. The high forces and blade action may cause potential problems with shredding the fibers during the mixing process. Irregular fiber lengths can cause high variability in material properties.

The most common method for wood-plastic compounding uses a twin screw extruder. This machine combines wood filler and plastic resin using two commingling screws. The screws produce shear forces that blend the two materials while cleaning screw surfaces to increase mixing and fiber distribution. The twin-screw extruder also removes volatile gases and can be adapted for other mixing applications. Variables include screw rotation direction, screw design, feeder location, and the machine settings (e.g., screw speed, temperature, feed rate, etc.). Similar to the kneader, the twin screw machine is modular and screw length can be adjusted. The twin screw design minimizes high peak shear values, making it ideal for fiber compounding operation.

Regardless of the compounding method, the mixed material is extruded from the machine in strands that must be cooled. A water bath or forced air are two common cooling

methods. After the strands of material are cooled, they are cut with a pelletizer and collected for use.

2.4.3 Forming Methods

Manufacturing plastic products can be accomplished by a variety of methods. Most processes use a form of extrusion, compression, or injection. The optimum manufacturing method often is dependent on the product itself. For example, a solid plastic part with a complex three dimensional geometry is best produced by injection molding. Conversely, products that have a constant cross section are most effectively formed using an extruder.

2.4.3.1 Compression Molding

This method uses two horizontal plates to compress the plastic material into the desired shape. Raw material is fed into the press and heated during compression. After the press is closed cooling can take place within the press or removed to an air cooling unit. This method uses relatively low cost equipment that is readily available. An advantage for wood-plastic composites is that the feedstock does not need to be mixed again causing further breakdown of the fibers. The press is not ideal for large scale production due to long cycle time. Another disadvantage is the high amount of waste product from flashing.

2.4.3.2 Injection Molding

Injection molding is perhaps the most widely used of all plastic processing methods. The machine consists of a head barrel with a rotating screw inside. The pelletized feedstock is melted within the barrel and forced into a clamped water cooled mold under extremely high pressure. After the plastic solidifies, the mold is separated and the finished product is ejected.

This method is very cost effective in production. But, the capital investment for the machinery is very high. The mixing barrel insures that all of the material will be melted producing a uniform and well bonded product. Difficulties can occur using resins with a low melt flow index, or high viscosity, and therefore, injection molding requires significant development time in selecting resins and fine tuning the process.

2.4.3.3 Extrusion

Extrusion is similar to injection molding, except there is no mold. Melted plastic pellets are forced or extruded directly out of the mixing barrel through a die. Various dies can be substituted on the extruder to produce different cross sections. The extruded product is cooled and cut to the desired length. Sheet extrusion is a variation of this process where continuous flat sheets of plastic are extruded in various widths. Sheet extruders can produce large uniform panels.

2.4.3.4 Blow Molding

Blow molding is closely related to injection molding, with the exception that the final product is hollow. Pellets are heated within the mixing barrel and the melted plastic is extruded vertically as a tube into mold. The two halves of the mold close and compressed air inflates the plastic tube forcing it outward like a balloon. The plastic conforms to the inside shape of the mold with a hollow internal section. The product is cooled and ejected.

Similar to extrusion, blow molding requires high melt strength plastic. Equipment and production are generally more expensive than found with injection molding machinery. Cycle times are typically slower than injection molding. This process is ideal to designs consisting of hollow shapes such as milk containers.

2.4.4 Cooling

Cooling is an important operation in plastic manufacturing regardless of the forming method used. Thermoplastics have a high thermal conductivity and therefore cool quite slowly. As a section increases in size, a proportional amount of cooling time is required. If cooling is not done in a controlled environment, differential thermal stresses may be induced giving unbalanced shrinking resulting in severe panel warping. Chilled molds and air are the two most common cooling methods.

2.5 Testing Standards and Accelerated Aging

2.5.1 Testing Standards

A wood-plastic composite panel testing standard would be the appropriate choice for evaluating the material in this study. Since there is no such standard, a substitute was selected. Testing standards exist for both plastic products, including plastic lumber, and conventional wood-based panel products. There are no plastic standards that thoroughly address material properties critical in conventional structural building applications. Also, plastic testing standards are limited to ultraviolet ray degradation for accelerated aging, and do not include the cyclical aging effects that influence wood but not plastic properties. The wood panel products testing standard (ASTM D1037) addresses many structural properties and includes a cyclical accelerated aging process.

The ASTM D1037 standard was used for this study. A portion of the study is dedicated to comparing wood-plastic composite panels to conventional wood-based panels. The majority of testing for the conventional panels applied the ASTM D1037 standard. Thus, it would appear to be logical to use the same testing conditions for a direct comparison.

2.5.2 Accelerated Aging

An important component of this study was to evaluate the effects of accelerated aging on wood-plastic composite panels as defined in ASTM D1037. The best way to evaluate the aging of materials would be to leave the material outside subjected to weathering for a long period of time. Although this type of test would provide accurate results for outdoor aging, it is not very practical. The ASTM D1037 standard suggests a procedure that subjects a wood-based panel to various temperature and moisture conditions to accelerate aging. This procedure has been used extensively to evaluate the aging response of common wood-based panel materials, such as hardboard, particleboard, and oriented strandboard (OSB). This process can not be taken as a duplication of actual weather conditions applied for many years. The natural environment does not produce steam at 200°F or have air temperatures that fluctuate 200°F as indicated in the standard. Nonetheless, this method offers an established process for simulating the aging of panel materials and offers comparative measure against commonly used building materials.

Other studies have been conducted attempting to shorten the aging process from the three-week duration of the ASTM D1037 test, however, the full length protocol was used in this study. Also, the longer process was basis for comparing alternative aging methods (McNatt, 1993). It has been shown that there is a high correlation for modulus of rupture between laboratory accelerated aging and actual outdoor aging for wood-based panels (River, 1994). The ASTM D1037 process does not provide results equal to actual aging, but it surely can be used as a means to measure relative material degradation imposed by fluctuating temperature and moisture conditions found in many environments.

Chapter 3 – Material Preparation

This section addresses the materials chosen for evaluation in this study. Also, the processing method, the panel forming, and the specimen preparation are included.

3.1 Material Selection

The thermoplastic resins LDPE and PP were used in this study. These resins along with HDPE are ideal for wood-plastic composite panels. They all have a low melting point allowing thorough mixing between the wood flour and the plastic without thermally degrading the fibers. These three plastics are low in cost and readily available in the recycling market (English, 1996). Considerations also have been made for selecting and developing resins that are flexible for a variety of manufacturing process.

Pine wood waste ground to a 40 mesh (0.0167-in (0.425mm) opening size) wood flour was used as the filler. This material is common on the recycling market, but other species of wood fillers can be substituted. All materials for this study originated from post-consumer recycling sources. Typically, it can not be expected to exclusively receive specific wood species especially in post-consumer markets.

3.2 Panel Manufacturing

The panel manufacturing for this study was conducted at the Forest Product Laboratory (FPL). A pelletized feedstock, produced with a twin screw extruder by North Woods Plastics was used. There were several pellet blends ranging from 20 to 60 percent wood flour by weight. Panels were also studied that did not include any wood flour in the material composition. Two full-sized 4'x 8' panels were obtained from Recycled Plastics Industries made from post-consumer thermoplastic HDPE flakes. The 100 percent plastic sheets were compressed in a heated press to half-inch stops.

The compounded pellets were used to manufacture panels in a laboratory press shown in Figure 3.1. The panels were manufactured at the FPL and were 20-in x 22-in x ½-in

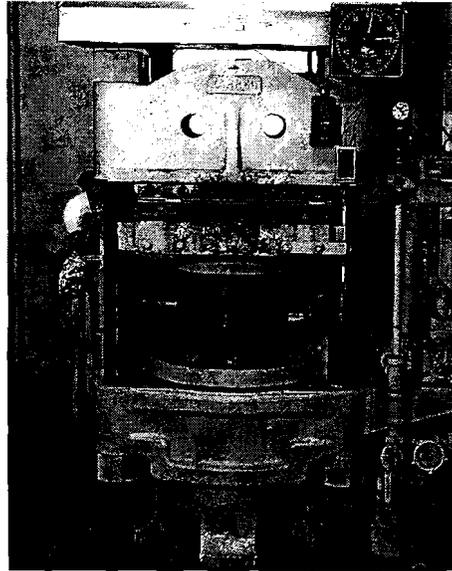


Figure 3.1 – Heated Laboratory Press used to Form Wood-Plastic Composite Panels at the FPL Melt Blend Laboratory

in size. Two heated platens were pressed together between a half-inch frame defining the dimensions of each panel. The pressing times and pressure varied with the amount of wood flour. As the percentage of added fiber increased, the melt-flow index decreased requiring additional pressure and pressing time to properly form the panels. In all cases, the press was heated to 200°C and cooled to approximately 60°C before the panel was removed from the press. Cooling took approximately 15 minutes and did not vary much between panel formulations. Table 3.1 lists the press settings for each material composition.

Table 3.1 – Material Content and Manufacturing Specifications

Percent Wood Flour	0	20	30	40	50	60
Percent HDPE	100	0	0	0	0	0
Percent LDPE	0	40	35	30	25	20
Percent Polypropylene	0	40	35	30	25	20
Pressing Time, min.	15	17	20	20	25	30
Pressure, psi (MPa)	1500 (10.3)	700 (4.8)	1000 (6.9)	1000 (6.9)	1000 (6.9)	1500 (10.3)

The primary disadvantage in manufacturing panels using compression lies in the large volume of material to heat from the press platens. If enough heat is not dispersed through the material, the plastic component can not flow bonding the pellets together. At higher wood flour percentages (i.e., 50, 60) complete plastic flow was not always achieved. To alleviate the problem, the 60 percent wood flour pellets were preheated for two hours at 100°C. Providing the initial increase in temperature allowed the pellets to fully melt forming a uniform product. It first appeared that only the 60 percent panels had problems achieving a uniformly melted cross section. After specimens were cut from the panels, some specimens revealed a fissure or thin layer of poorly melted pellets at the neutral axis of the panel. This can be explained considering that the fissure was the furthest area from the heat source. As will be described later in Chapter 5, this lack of bonding had some effect on panel properties.

Producing large panels may become problematic when using a conventional heated press, since the press size must be identical to the desired sheet dimensions. A standard 4 x 8-foot panel requires a large press and a high amount of heat distribution to achieve the proper melting temperature over the entire panel surface area. Realistically, the heated surface of the press will vary substantially. A differentiation in surface heat will produce panels that have discrepancies in pellet bonding due to variable temperatures over the press surface. Inconsistencies in the panel processing may lead to unpredictable and inconsistent material properties and dimensions.

Based on these observations, a heated press is not recommended for manufacturing panels from pellets with a wood filler content higher than 40 percent. Other processing

methods such as extrusion or injection molding insure that all of the material attains the specified temperature and is thoroughly mixed during the manufacturing process.

3.3 Specimen Preparation

Specimens were cut from each panel according to the dimensions required in ASTM D1037 (see Appendix B). Wood-based panel products often have directional properties. Because wood-plastic panels are isotropic, no effort was made to cut specimens along a particular axis. Each specimen was labeled with the percentage of wood flour, panel number, and specimen number. Table 3.2 indicates the size and number of specimens evaluated in this study.

Table 3.2 – Size and Number of Test Specimens Used in Each Test

Test	Number of Specimens per Panel Formulation	Specimen Dimensions (width x length x thickness)
Bending	10	3-in x 14-in x 0.5-in
Tension	10	2-in x 12-in x 0.5-in
Edgewise Shear	10	3.5-in x 10-in x 0.5-in
Hardness	10	3-in x 6-in x 1-in
Moisture Absorption	10	6-in x 6-in x 1-in
Thermal Expansion	10	3-in x 11.75-in x 0.5-in
Screw Withdrawal	20	3-in x 4-in x 0.5-in
Nail Withdrawal	20	3-in x 6-in x 0.5-in
Lateral Nail Resistance	20	3-in x 6-in x 0.5-in
Nail Head Pull Through	20	3-in x 6-in x 0.5-in

All specimens were conditioned at 74°F (23°C) and 65 percent relative humidity for at least three months. The effect of conditioning has not been fully explored for wood-plastic composite panels, however, the material performance is not expected to vary greatly with conditioning as it might with some conventional wood products.

3.4 Accelerated Aging

The accelerated aging process involves six condition changes for six continuous

cycles. The steps are listed in Table 3.3. Specimens were spaced ½-in apart in four large racks as shown in Figure 3.2. The racks were stacked vertically throughout the aging

Table 3.3 – Conditions for the ASTM D1037 Accelerated Aging Process

Step	Condition	Temperature, °F (°C)	Duration, Hours
1	Water Soak	120 (49)	1
2	Steam	200 (93)	3
3	Freeze	10 (-12)	20
4	Dry Heat	210 (99)	3
5	Steam	200 (93)	3
6	Dry Heat	210 (99)	18

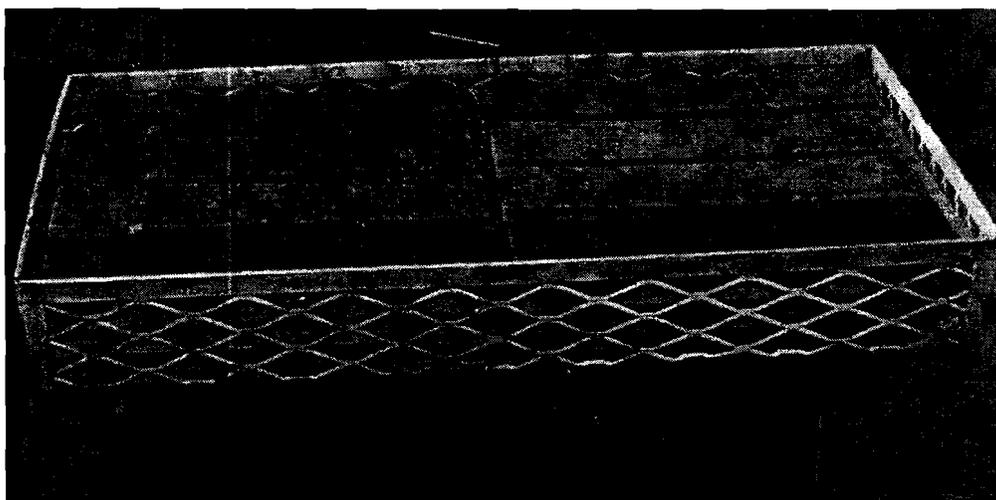


Figure 3.2 – Accelerated Aging Rack, Bending Specimens, Spaced at ½-in Positioned in a Stainless Steel Rack.

process. Since the placement of the specimens could effect the aging of the material, racks were rotated to different levels based on a schedule to allow for equal exposure of each rack at each level (see Appendix B). For example, the water soak step exerts greater pressure on the lowest specimens in the tank. The water soak and steam steps were performed in the same tank pictured in Figure 3.3. Conditions were maintained using an air-pressurized controller governing a steam supply. Temperature was charted to insure the set conditions were maintained while the tank was not attended. Previous studies typically investigated only a few properties to characterize a materials ability to withstand harsh conditions. This

study used a duplicate set of aged specimens in each test to quantify several material properties.



Figure 3.3 – Accelerated Aging Tank Used for Steam and Water Soak Conditions

Chapter 4 – Experimental Testing

As described in Section 2.5, all experimental tests were conducted in accordance with ASTM D1037. The parameters for each test are outlined within the corresponding subsections.

4.1 Bending

Static bending tests were performed on a screw driven machine over a simply supported span with a center point load as shown in Figure 4.1. The bending specimens

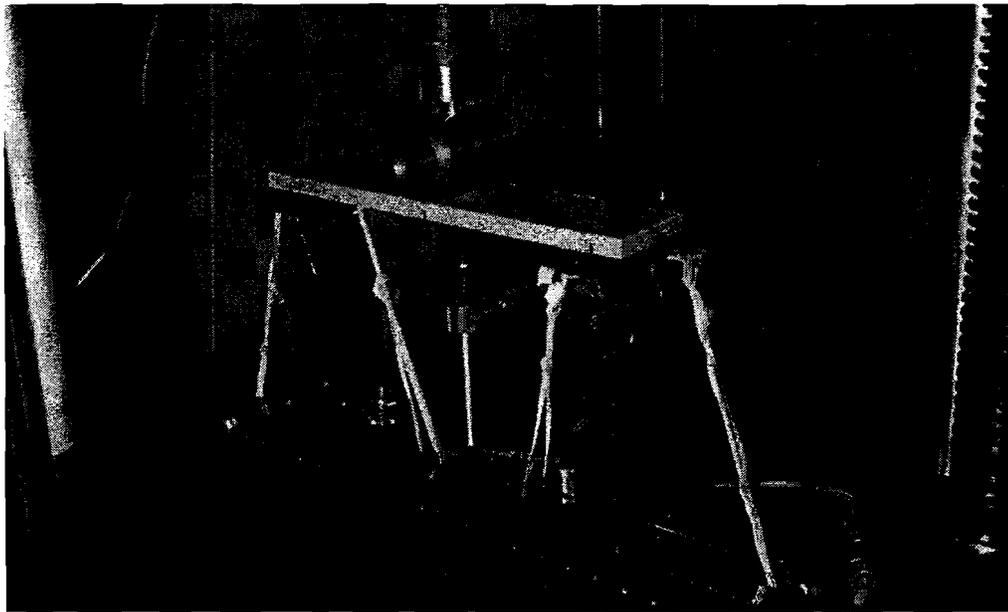


Figure 4.1 – Center Point Bending Test Setup with a 12-in Span

had nominal dimensions of 3-in x 14-in x ½-in. Supports consisted of a top and bottom plates separated by rollers to provide free movement in the longitudinal direction. The bottom plates rested on knifed supports to allow rotation. A +/-1 inch linear variable differential transducer (LVDT) was used to measure vertical deflection at the midpoint of the specimen width and length. Large deflections were expected for the specimens with little or no wood flour filler. Therefore, the entire 2-in range on the LVDT was used to

record vertical movement. A crosshead speed of 0.36 in/min was used. Because polymers tend to creep, measured deflection can vary with the speed of loading. Preliminary testing indicated that deflection did not vary significantly with speeds higher than 0.6 in/min. For this reason, the speed chosen was at the upper end of the 0.24 +/- 50% in/min range suggested by the standard.

The dimensions of the test specimen were chosen in order to minimize shear deformations. An equal number of specimens were tested for each wood percentage ranging from 0-60 percent. Table 4.1 summarizes the specifications of the static bending test.

Table 4.1 – Bending Test Summary

# of Unaged Specimens per group	# of Aged Specimens per group	Speed of Test (in/min)	Specimen Dimensions	Load Cell Capacity (pounds)	Maximum Measurable Deflection	Span
10	10	0.36	3" x 14"	500	2"	12"

4.2 Tension

Tension tests were conducted to obtain the tensile properties of wood-plastic composite panels. A 10,000 lb. capacity MTStm screw-driven testing machine was used with a 10,000 lb. load cell. A 2-in by 12-in dogbone specimen was used as specified in the ASTM D1037 standard. A 1-in extensometer was secured to the necked portion of the test specimen to measure material strain. The extensometer was removed when plastic deformation initiated. Table 4.2 lists the extensometer removal point for each wood percentage.

Table 4.2 – Strains for Removing Extensometer During Tension Testing

Wood %	Removal Point Strain, in/in
0	0.010
20	0.007
30	0.006
40	0.005
50	0.004
60	0.004



Figure 4.2 – Tension Test using a 1-in Extensometer

In a slight variation to the standard, bolted grips were chosen over self-tightening grips to decrease the potential of the specimen slipping. The specimens were cut 2 inches longer than specified in the standard to increase the gripping surface. Table 4.3 summarizes the test specifications used.

Table 4.3 - Tension Test Summary

# Standard Specimens per group	# Aged Specimens per group	Speed of Test (in/min)	Specimen Dimensions	Necked Cross Section Nominal Dimensions	Gage Length
10	10	0.15	2" x 12"	0.5" x 1.5"	1"

4.3 Edgewise Shear

The edgewise shear test, often referred to as panel shear, evaluates the shear normal to the plane of the panel. The shear test was performed on the same machine used for the tension test. Steel rails were bolted to the specimen to allow edgewise shear loading to the

sample as shown in Figure 4.3. Four 7/16-in diameter holes were drilled on each side of the specimen and eight 3/8-in diameter bolts were used to secure the rails to the specimen. The



Figure 4.3 – Edgewise Shear Test using Steel Loading Rails, V-notched Members (top and Bottom) Resting on a Spherical Bearing Block

rails were securely tightened to eliminate the possibility of the specimen slipping during the test. Two V-notched members held the rails in place. A spherical bearing block was placed under the bottom V-notched member to uniformly distribute the load. Table 4.4 lists the testing specifications.

Research conducted at the FPL has shown that this test provides reasonably uniform shear distribution through the length (vertical dimension) of the specimen (McNatt, 1969). It was also found that this method accurately determined the edgewise shear strength when compared to test results of actual structures.

Table 4.4 – Edgewise Shear Test Summary

# Unaged Specimens per group	# Aged Specimens per group	Speed of Test (in/min)	Specimen Dimensions	Bolt Diameter in Rails
10	10	0.02	3.5" x 10"	3/8"

4.4 Hardness

The hardness test measures the amount of force required to deform the material of the test specimen half the diameter of a steel sphere. To accomplish this, a modified Janka ball was used (ASTM, 1992). A collar and pin were positioned on the shaft above the Janka ball. When half of a diameter of material deformation was reached, the collar contacts the shaft causing an increase in the loaded surface area. When this occurs, the load vs. deflection curve sharply increases clearly indicating the load at one-half the ball diameter (see Appendix A). The results of this test can be used to compare the peak loads with other materials such as wood flooring. While this test does not provide specific engineering criteria, it does give a designer comparative performance to other materials. Refer to Figure 4.4 for the test setup.

According to ASTM D1037, a one-inch thick specimen is required for the hardness test. Therefore, two half-inch specimens were glued together to achieve the proper thickness. Thermoplastics are generally not an easy material to bond together. Two types of adhesives, an epoxy and a polyurethane, were evaluated. Both types of bonds withstood two cycles of accelerated aging. After inspecting the glue lines and separating the intact specimens, it was evident that the epoxy bonded better than the polyurethane. Apparently, the low moisture content of the composite did not provide enough water for the

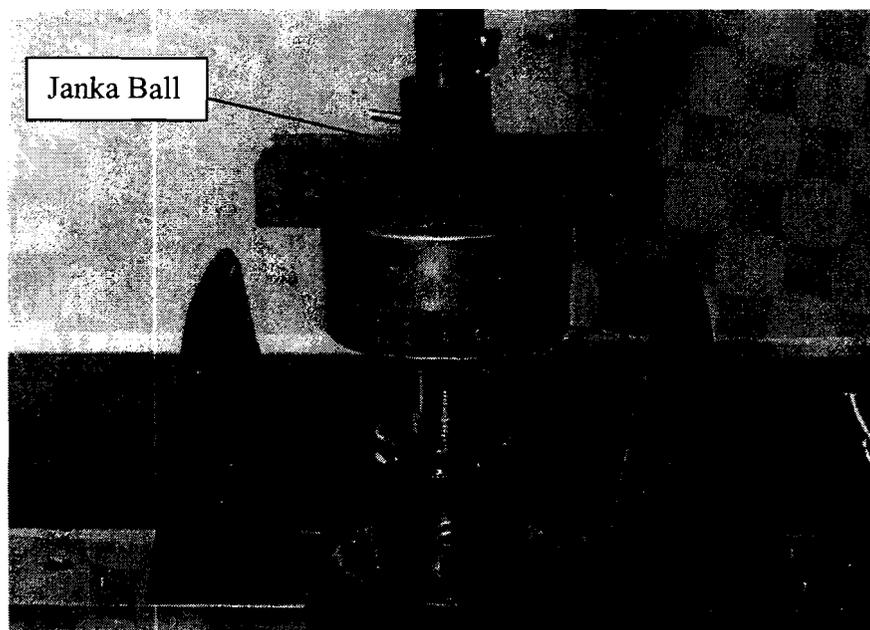


Figure 4.4 – Hardness Test with a Modified Janka Ball Positioned to Penetrate the Specimen Surface. Note the tightening collar just above (member with the largest diameter).

polyurethane to properly bond. Water was added during the application of the polyurethane to compensate for the composite material's low moisture content when compared to wood. The epoxy does not require water and therefore gave more consistent results than the polyurethane. Because of the difficulty bonding, the aged hardness specimens were glued after the aging process to minimize delamination.

Table 4.5 – Hardness Test Summary

# of Unaged Specimens per group	# of Aged Specimens per group	Speed of Test (in/min)	Specimen Dimensions	Modified Janka Ball Diameter
10	10	0.25	3" x 6" x 1"	0.444"

4.5 Moisture Absorption

Moisture absorption tests evaluate a material's ability to resist the intake of water and quantify the dimensional changes due to submersion in water. Specimens were conditioned at 72°F (22°C) and 65% relative humidity for five months prior to testing.

Initial measurements of the conditioned specimens were taken to determine initial volume and weight. The samples were submerged horizontally under one-inch of distilled water. Measurements were repeated after 2 hours and 24 hours to determine absorption characteristics. Changes in thickness can be inconsistent, so measurements were taken at the midpoint of each side of the specimen one inch in from the edge. The four measurements were averaged to calculate the material thickness. Table 4.6 lists the testing specifications.

Table 4.6 – Moisture Absorption Test Summary

# of Standard Specimens per group	# of Aged Specimens per group	Conditioning Room Temp. / Humidity	Time Duration at Measurement, Hours	Specimen Dimensions
10	10	72° F / 65%	0, 2, 24	6" x 6"

A specific gravity test was conducted after the specimens were removed from the water bath. Specimens were oven dried at 217°F (103°C) for a 48-hour period. Using the initial conditions and the oven dry weight, specific gravity and moisture content were calculated.

4.6 Thermal Expansion

Tests were performed on both standard and aged specimens to quantify the thermal linear expansion of wood-plastic composite panels. An Aminco Climate Lab was utilized for generating the various thermal conditions. This apparatus precisely controls the temperature and relative humidity with refrigeration and heating units. Water is heated in the conditioning chamber to a set dew point temperature. Passing air is saturated with the water that continues through a heater set at a dry bulb temperature. When both the dew point and dry bulb temperature are controlled only a corresponding humidity level can

result. Temperature was varied from 62°F (16.7°C) to 140°F (60.0°C) while maintaining a constant relative humidity of 65% as shown in Table 4.7.

Table 4.7 – Thermal Expansion Test Summary

# of Unaged Specimens per group	# of Aged Specimens per group	Temperature Variation, °F (°C)	Relative Humidity	Specimen Dimensions
10	10	62, 72, 100, 120, 140 (16.7, 22.2, 37.8, 48.9, 60)	65%	3" x 11.75"

4.7 Fastener Tests

4.7.1 Screw Withdrawal

The screw withdrawal test determines the ultimate load to pull a screw from the panel product. A No. 10 sheet metal screw was driven .67-in into each specimen immediately before the testing process. Screws were driven prior to aging for the aged test case. Stainless steel screws were used to resist corrosion in the aging process. A 1/8-in diameter pilot hole was drilled ½-in into each specimen.

Similar to the hardness test, specimens had to be built up to a one-inch thickness as shown in Figure 4.5. Unlike the hardness test, screw withdrawal specimens are required to be aged after bonding because the fastener must be imbedded into the material before the aging process. A bonding agent could not be found that was capable of withstanding the full aging exposure. The zero percent specimens separated during the aging process though, the remaining groups withstood the aging effects for five cycles. After the fifth cycle, some of the 20% wood flour specimens began to delaminate. All of the higher wood content samples held together through the entire aging process. Screw penetration in the second layer of the specimen was limited to the tapered portion of the screw. This segment of the screw does not provide much holding capacity and therefore, it is anticipated that the

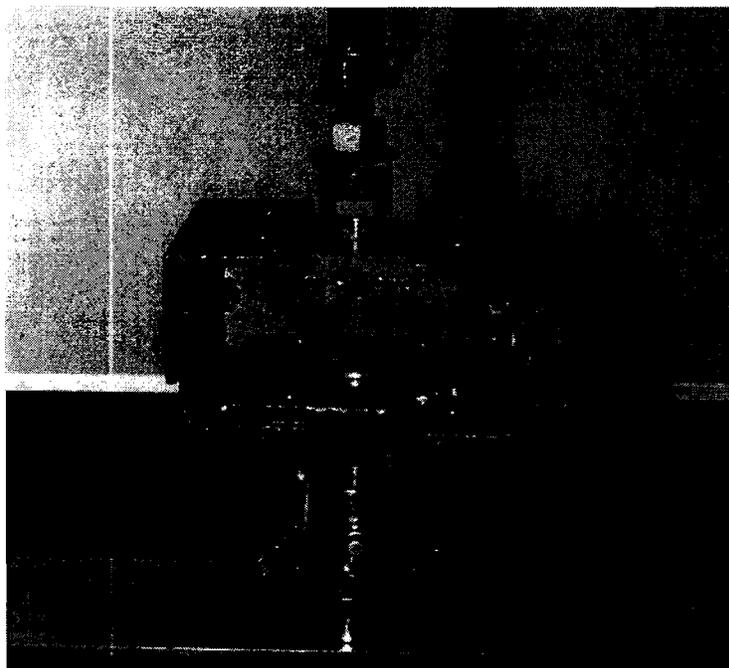


Figure 4.5 – Screw Withdrawal Test using a No. 10 Sheet Metal Screw, Type AB with a One-inch Thick Specimen.

results for the delaminated specimens were not significantly altered. Table 4.8 lists the testing specifications.

Table 4.8 – Screw Withdrawal Test Summary

# of Unaged Specimens per group	# of Aged Specimens per group	Screw: No. 10 Type AB Length: 1"	Threads per Inch	Specimen Dimensions (w x L x t)	Testing Speed (in/min)	Predrill Diameter
20	20		16	3"x 4"x 1"	0.6	1/8"

4.7.2 Nail Withdrawal

The objective of the nail withdrawal test is similar to the screw withdrawal test. The peak load is found when a six-penny nail is pulled free from the panel specimen. There are two main differences between the screw withdrawal test and the nail withdrawal test. First, the test specimen thickness is ½-in thick for the nail withdrawal sample and 1-in thick for the screw withdrawal sample. Second, the nail is driven ¾-in through the panel instead of only being embedded 0.67-in into a 1-inch sample.

Nails were hand driven immediately before testing to a distance such that the exposed length of the nail was equal on both sides of the specimen. Half of the nail withdrawal specimens were predrilled. A 3/32" pilot hole was used for the predrill case, which is equivalent to 80% of the nail diameter. Nails were driven prior to aging for the specimens in that category. The aged specimens were nailed approximately five months prior to testing.

All nails were plain shank and galvanized with a diamond point. The nail diameters were measured to calculate the surface area in contact with the panel. It was found that the variation in diameter was approximately 0.001 inches and therefore would not effect the resulting withdrawal load.

The accelerated aging process caused some corrosion to the nails as shown in Figure 4.6. Refer to Table 4.9 for the complete testing specifications and Figure 4.7 for a visual

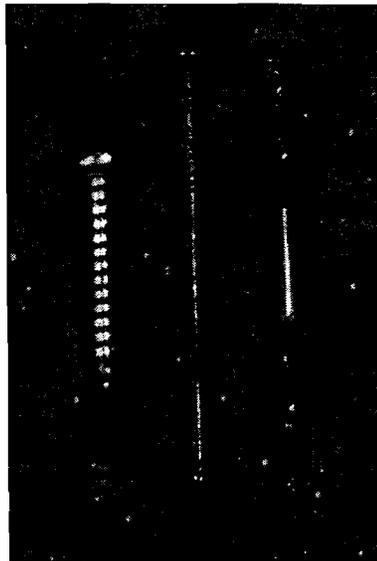


Figure 4.6 – Fasteners Used in Tests, left: Screw Withdrawal (No. 10 Type AB Sheet Metal Screw), middle: Nail Withdrawal (six-penny common nail), right: Aged Nail From the Nail Withdrawal Test. Note that at mid length is where the nail was embedded through the material.

representation of the test.

Table 4.9 – Nail Withdrawal Test Summary

# Unaged Specimens per group	# Aged Specimens per group	Speed of Test In/Min	Type of Nail: 6 Penny Common Length: 2"	Pilot Hole Diameter	Specimen Dimensions
20	20	0.06	Ave Dia: 0.117"	3/32"	3" x 6"

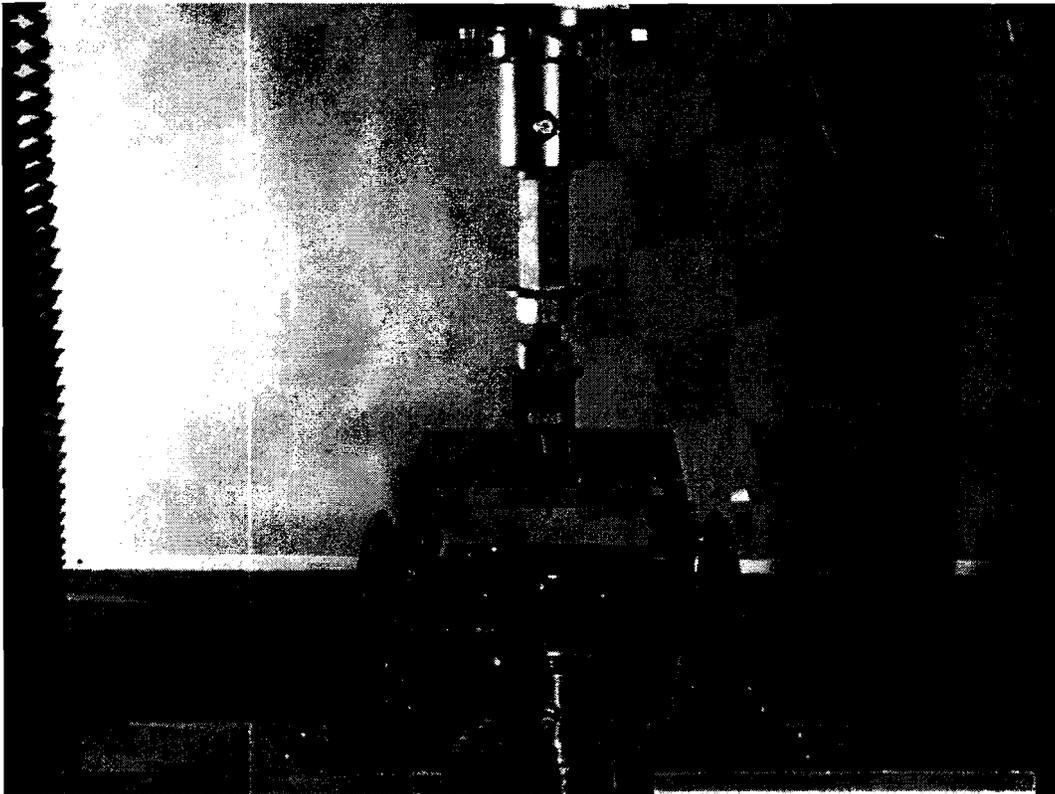


Figure 4.7 – Nail Withdrawal Test Using a Six-Penny Common Nail

4.7.3 Lateral Nail Resistance

The lateral nail resistance is the peak load a nail can resist when pulling it laterally through the panel. For this study, fasteners were driven $\frac{1}{2}$ " from the edge of the specimen as shown in Figure 4.8. Originally, half of the specimens were intended to be predrilled. Preliminary investigations indicated that the higher wood percentage panels without a pilot hole cracked from driving the nail into the sample. Therefore, all remaining specimens were predrilled with a pilot $\frac{3}{32}$ -in diameter hole.

The lateral nail resistance specimen size designated in the ASTM standard was found to be too wide to fit in the available test grips. The specimens were necked down at the gripping end to fit in the available tensile grips (see Figure 4.8).

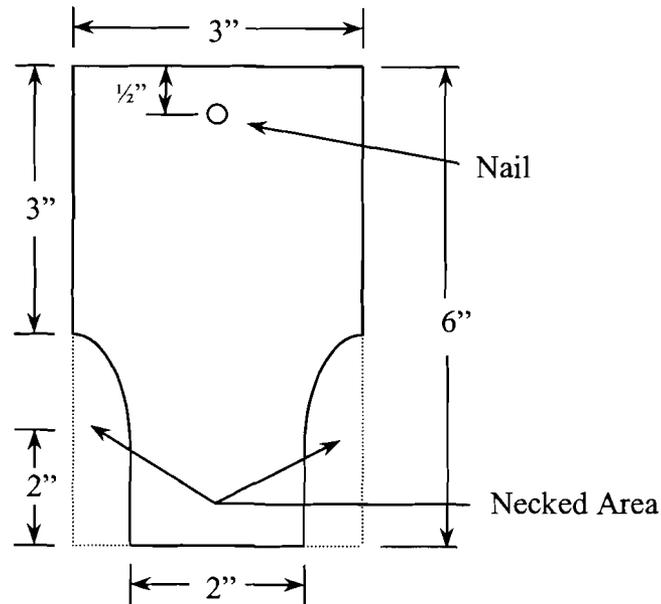


Figure 4.8 – Modification to the Lateral Nail Resistance Specimen to Allow for the Use of 2-inch Grips.

The nail holding jig shown in Figure 4.9 has two plates that can be adjusted to fit the sample thickness. A clearance was maintained between the specimen and the plate to insure the gripping device did not contact the specimen face causing an additional friction force. The bottom grip was pinned to the clevice to allow rotation in the direction parallel to the panel surface. Allowing rotation insures that the force on the nail is always perpendicular to the specimen edge. Table 4.10 lists the test specifications.

Table 4.10 – Lateral Nail Resistance Test Summary

# of Unaged Specimens per group	# of Aged Specimens per group	Speed of Test In/Min	Type of Nail: 6 Penny Common Length: 2"	Pilot Hole Diameter	Unmodified Specimen Dimensions
20	20	0.25	Ave Dia: 0.117"	3/32"	3" x 6"

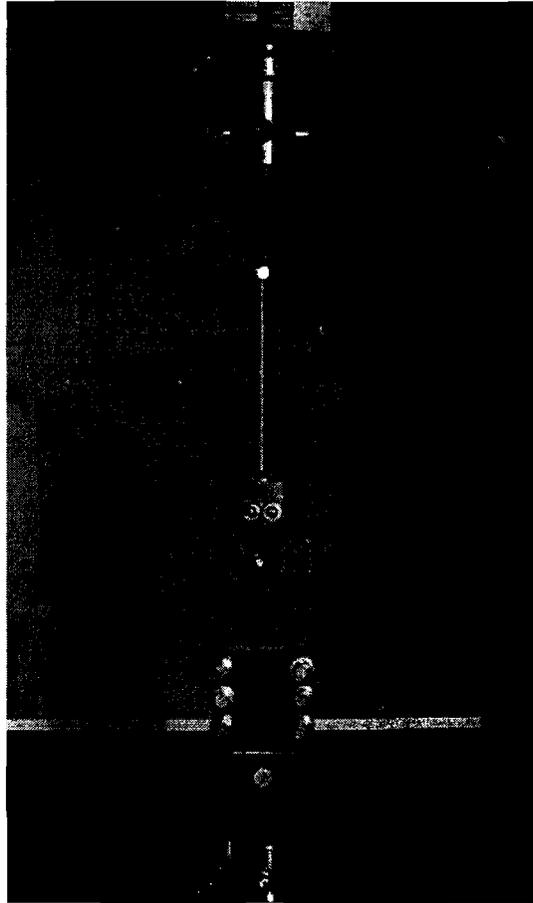


Figure 4.9 – Lateral Nail Resistance Test using a six-penny common nail and a ½-in wide fixture for holding the nail. Note the necked portion of the specimen near the top of the bolted grip.

4.7.4 Nail Head Pull Through

A third nail test investigated the force required to pull the fastener head through the panel material. A special device was made for gripping the nail by the shank as shown in Figure 4.10. The clamp was secured with six bolts to tighten two plates with a V-notch cut out where the nail inserts from the bottom end. Three set screws are located in the notch. When tightened, they embed into the nail creating a secure grip.

The effect of predrilling was explored for half of the samples as described in the nail withdrawal test. The nails were set immediately before the test was performed except for

the accelerated aging samples. Table 4.11 lists the specific testing parameters used for this test.

Table 4.11 – Nail Pull Through Test Summary

# of Unaged Specimens per group	# of Aged Specimens per group	Speed of Test In/Min	Type of Nail: 6 Penny Common Length: 2" Ave Dia: 0.117"	Pilot Hole Diameter	Specimen Dimensions
20	20	0.06		3/32"	3" x 6"

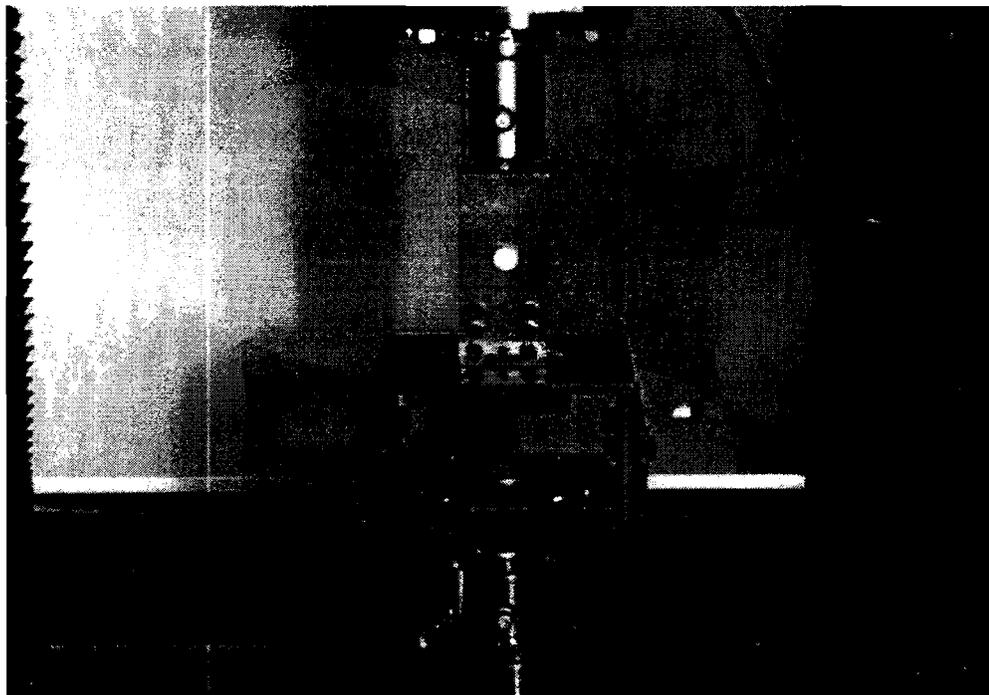


Figure 4.10 – Nail Head Pull Through Test with a 3-in Diameter Opening in the Top Plate. The nail is secured within the jig by three setscrews between two vertical rows of bolts to hold fixture plates together.

Chapter 5 - Results and Discussion

This section contains the results and discussion from the testing methods described in Chapter 4. Typical load versus displacement curves from each test are included in Appendix A. Simple equations are used to describe material property trends where practical. Only equations with a r^2 value of 0.75 or higher were accepted as a fit to the data which lies within the range for a strong correlation for engineering and scientific applications (Devore, 1995). All sections consider the effects of wood filler content and the accelerated aging exposure.

There were some overlying issues found in many of the test results. The first is a material defect, as denoted in some of the test summary tables. Processing defects were found in many test sample groups, but were predominate in one batch of 50% wood filler panels. The main defect consisted of a layer of partially fused pellets at the neutral axis of the panel as shown in Figure 5.1. When present, this flaw resulted in significantly reduced

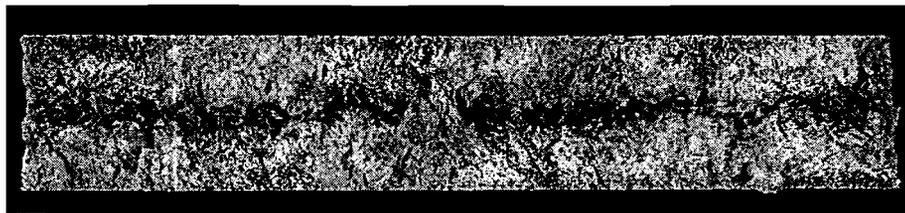


Figure 5.1 – Layer of Partially Bonded Pellets from Inadequet Melting During the Compression Molding Process.

material properties in nearly every test. Approximately 1 percent of the data points were removed from the data set when an obvious flaw was found. During the panel manufacture and specimen preparation, it was not obvious that the interior pellets were poorly bonded. Only after test failures similar to Figure 5.1, did flaws become apparent.

A second issue affected the 0% wood filler specimens. In some cases, this group of

samples did not exhibit expected trends when compared to the remaining test groups. This may be attributed to the difference in plastic resin. The plastic samples were made from HDPE, while the wood-plastic blends were composed of equal amounts of PP and LDPE. Because of manufacturing constraints of the industrial supplier, it was not possible to produce 100% plastic panels from recycled PP and LDPE resins.

Statistical analysis was performed to find the significance of aging on material properties that were considered as primary importance as described in the scope. A two-tailed t-test with equal variances was used to find the smallest significance level at which the means are considered to be equal which is known as the P-value. The P-values for each test are shown in a table near the end of each subsection. A small P-value denotes a low probability that the null hypothesis of equal means was rejected when it should have passed. Therefore, a high P-value gives reasonable assurance that the null hypothesis was correctly accepted. Statisticians typically use significance levels ranging from 0.01 to 0.1 when performing this type of statistical analysis (Devore, 1995). Consequently, a P-level greater than 0.1 should be considered high enough to accept the null hypothesis of equal means concluding that the means are not significantly different.

5.1 Bending

Bending tests were conducted to calculate the bending modulus of elasticity (MOE) and the modulus of rupture (MOR) for wood-plastic composite panels. Test data consisted of load and center point deflection values. These properties were considered to be of primary importance and therefore, include a statistical analysis of the aged and unaged data.

Specimen failure typically occurred directly under the load head, which is the location of the maximum moment. The failure was propagated on the tension (bottom) face

of the panel specimen as shown in Figure 5.2. The fracture surface typically revealed protruding wood flour particles in applicable specimens as shown in Figure 5.3.



Figure 5.2 – Typical Flexural Failure Resulting from the Center-Point Bending Test Located on the Tension Face of the Specimen. Note the vertical line represents mid-span.

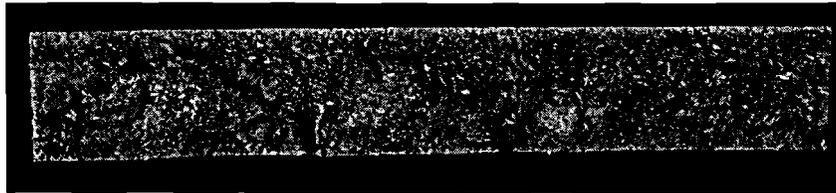


Figure 5.3 – Cross Section of a Typical Bending Failure. Note large amounts of wood particles represented by the light specs.

The maximum measurable deflection was 2 inches for the described test setup. All of the 0% wood filler specimens and some of the lower wood percentage specimens (i.e., 20%, 30%) did not fail in this range. For these cases, the initial MOE value could be calculated, but the MOR value was not reported. If the specimen were allowed to deflect an additional amount, higher loads would most likely result thus, increasing the MOR.

The initial slope of the load versus displacement data was calculated using a nonlinear curve fitting program, Tanh (see Appendix D). These slopes were converted to MOE values using the following equations from linear elastic beam theory.

Moment of Inertia, I, for a rectangular cross section of height h and width b is given by:

$$I = \frac{bh^3}{12} \quad (5.1)$$

Vertical Deflection, Δ , from a center point load on a simple span is given by the following equation:

$$\Delta = \frac{Pl^3}{48 \cdot MOE \cdot I} \quad (5.2)$$

where P is the center point load and l is the span length. Rearranging Equation 5.2 and substituting Equation 5.1 yields:

$$P = \frac{MOE \cdot 4bh^3 \cdot \Delta}{l^3} \quad (5.3)$$

Taking the derivative of Equation 5.3 with respect to Δ gives:

$$\frac{dP}{d\Delta} = \frac{MOE \cdot 4bh^3}{l^3} \quad (5.4)$$

or the initial slope of the load verses displacement curve. Solving for MOE results as:

$$MOE = \frac{l^3}{4bh^3} \cdot \frac{dP}{d\Delta} \quad (5.5)$$

Restated, the MOE equals the initial slope of the load vs. displacement curve multiplied by the constants corresponding to the geometry of each specimen. Table 5.1 summarizes the bending MOE test results. Figure 5.4 shows the MOE values for the standard and aged specimens.

Table 5.1 – Summary of Bending MOE Results

Percent Wood Flour	Unaged Specimens			Aged Specimens		
	n ^b	Mean MOE x 10 ⁶ psi (MPa)	COV ^a	n ^b	Mean MOE x 10 ⁶ psi (MPa)	COV ^a
0	10	0.13 (900)	0.03	10	0.14 (970)	0.03
20	10	0.17 (1170)	0.07	10	0.17 (1170)	0.08
30	10	0.22 (1520)	0.05	10	0.20 (1380)	0.05
40	10	0.24 (1650)	0.11	10	0.23 (1590)	0.10
50	8 ^c	0.24 (1650)	0.11	8 ^c	0.18 (1240)	0.06
60	10	0.25 (1720)	0.04	10	0.17 (1170)	0.04

a Coefficient of Variation

b Number of specimens used to calculate results

c Material flaw found in unreported specimens

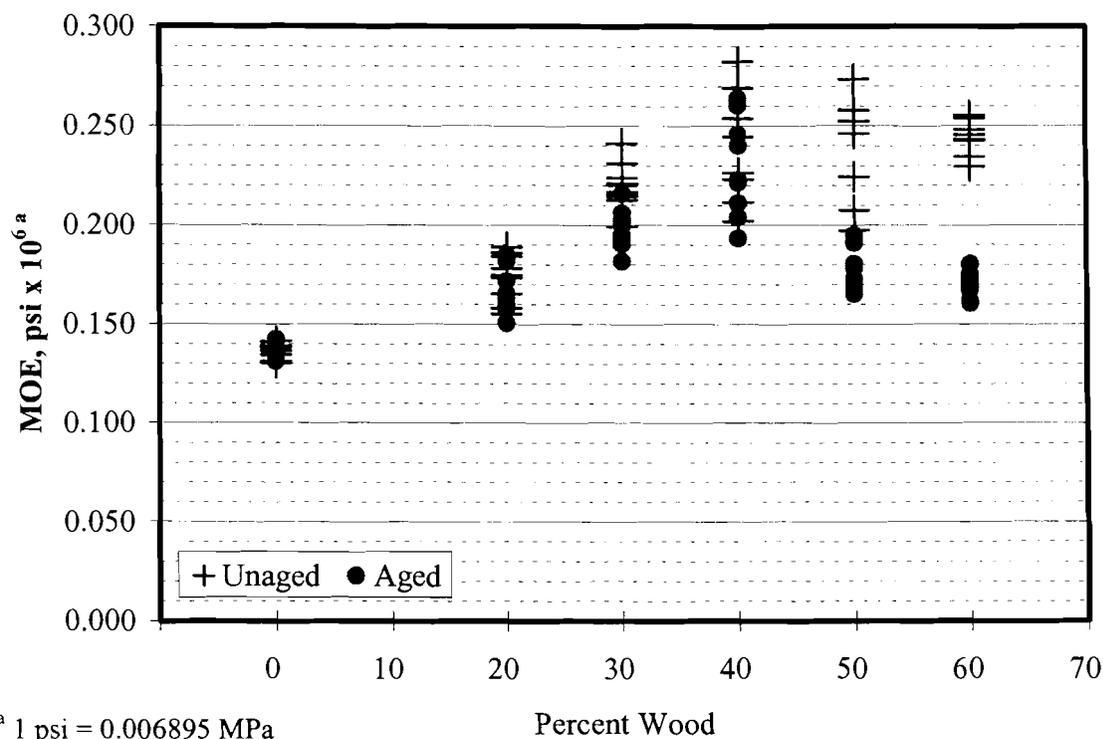


Figure 5.4 - Bending Modulus of Elasticity Results Comparison for Aged to Unaged Specimens

The MOR is the extreme fiber stress resulting from the peak load of the bending test.

Flexural stress, σ , in a beam is given by Equation 5.6 where M is the moment in the beam at that location and c equals the distance from the neutral axis to the extreme fiber.

$$\sigma = \frac{Mc}{I} \quad (5.6)$$

If M' is substituted for M as the moment from the peak load, the peak stress at the extreme fiber is the MOR or

$$MOR = \frac{M'c}{I} \quad (5.7)$$

Moment, M , at midspan with a center point load, P equals

$$M = \frac{PL}{4} \quad (5.8)$$

Substituting Equation 5.8 into Equation 5.7 for the moment value gives

$$MOR = \frac{P' Lc}{4I} \quad (5.9)$$

where P' refers to the peak load during the bending test. Figure 5.5 shows the bending MOR data and Table 5.2 summarizes the results. Figure 5.6 graphically shows the result of the accelerated aging exposure for the bending MOE and MOR.

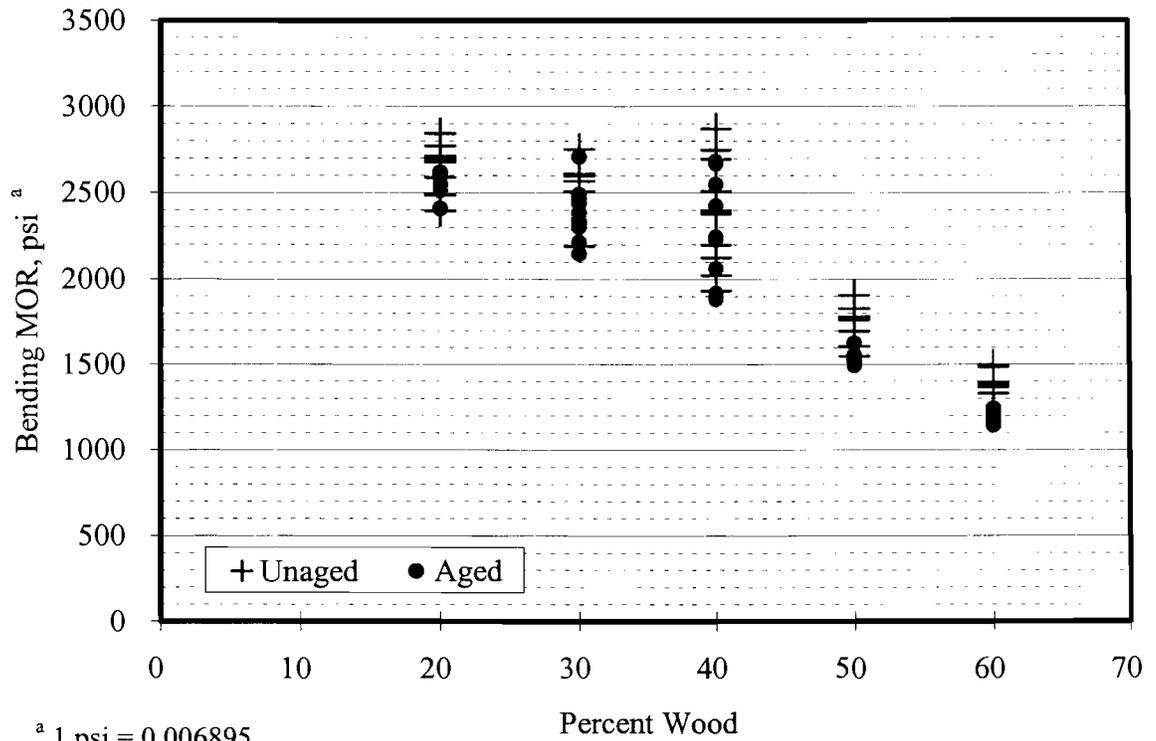


Figure 5.5 - Bending Modulus of Rupture Results Comparison for Aged to Unaged Specimens

Table 5.2 – Summary of Bending MOR Test Results

Percent Wood Flour	Unaged Specimens			Aged Specimens		
	n ^b	Mean MOR, psi (MPa)	COV ^a	n ^b	Mean MOR, psi (MPa)	COV ^a
0	0 ^d	NA	NA	0 ^d	NA	NA
20	9 ^d	2650 (18.3)	0.05	6 ^d	2500 (17.2)	0.03
30	9 ^d	2550 (17.6)	0.06	10	2400 (16.5)	0.07
40	10	2400 (16.5)	0.13	10	2300 (15.9)	0.13
50	8 ^c	1700 (11.7)	0.07	8 ^c	1500 (10.3)	0.03
60	10	1400 (9.7)	0.04	10	1200 (8.3)	0.03

^a Coefficient of Variation

^b Number of specimens used to calculate results

^c Material flaw found in unreported specimens

^d Peak load did not occur in unreported specimens

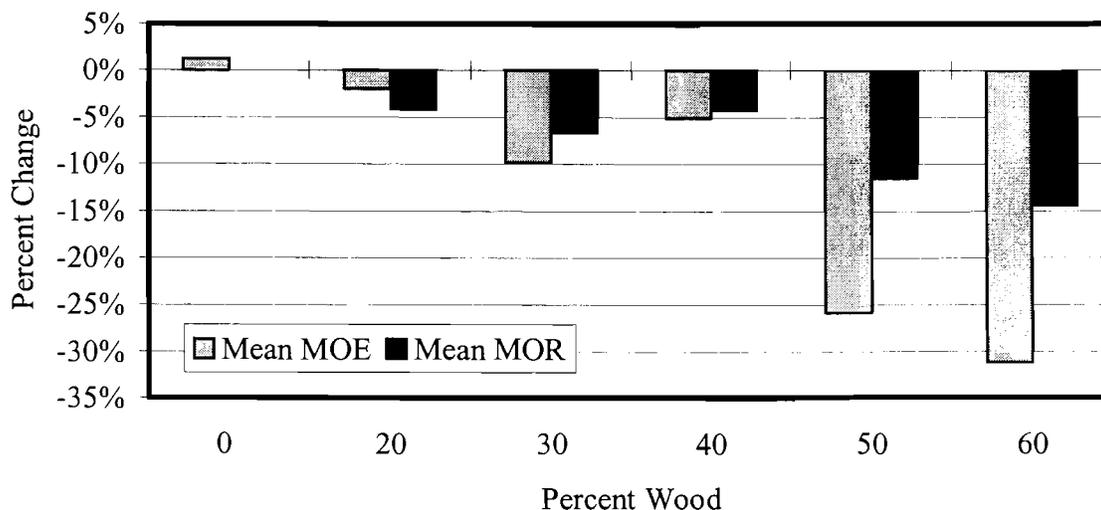


Figure 5.6 - Effect of Accelerated Aging Exposure on Mean Bending Results

Changing the wood filler ratio effected the bending properties for wood-plastic composite panels. The mean MOE increased by 90% when comparing 0% and 60% wood filler content. There were no simple equations found to accurately represent the change in MOE with wood percentage. Figure 5.7 shows the mean trends of the unaged bending data



Figure 5.7 - Trends in Mean Bending Modulus of Elasticity

presented in Figure 5.4. The most significant increase in MOE occurred between 20% and 40% wood content. Only a 4 percent change in the mean bending MOE occurred above 40% wood content.

As shown in Figure 5.8, the mean bending strength, MOR, decreased by 48% when comparing the 20% and 60% wood filler content results. The 0% wood filled panels did not fail and therefore no MOR value could be calculated. Similar to the MOE, there were no practical equations to represent the decrease in MOR. There appears to be a sudden decrease in the bending MOR changing from 40% to 50% wood filler content. This may be attributed to the forming difficulties associated with the two highest wood content groups. In general, the loss of bending strength results from additional fracture sites associated with more wood flour particles. This creates voids in the plastic material potentially allowing for tensile failures at lower loads.

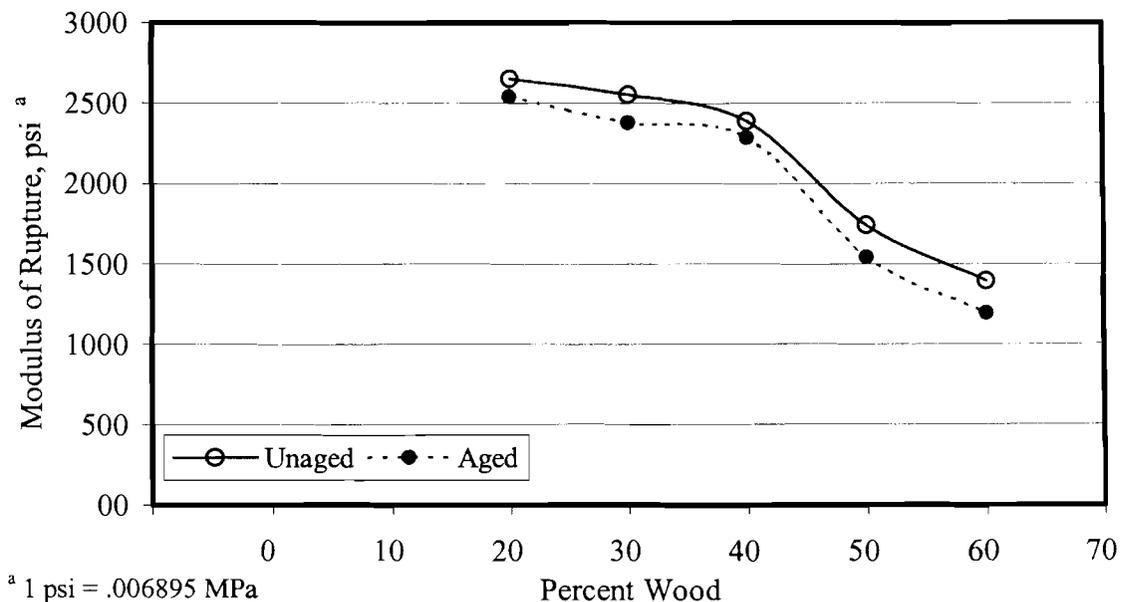


Figure 5.8 - Mean Bending Modulus of Rupture Trends

The accelerated aging exposure had a significant impact on the high wood content samples decreasing bending MOE mean values by approximately 30%. Table 5.3 shows the P-values for accepting the null hypothesis that the aged and unaged means are equal for bending MOE and MOR using a t-test. The mid-range specimens showed some loss in stiffness (about 5%), but were able to resist the aging effects somewhat better than the higher wood content specimens. The aging process did not significantly effect the bending MOE of the lower wood content panels. The accelerated aging exposure effected the mean MOR. On average, there was an 8% drop in MOR due to accelerated aging exposure. The statistical analysis shows that all means were significantly different except for the 40% wood filler specimens. Similar to the MOE results, 50% and 60% filled specimens showed the highest decrease in MOR.

Table 5.3 – T-test P-values of Equal Means for Aged and Unaged Bending Data

Wood Flour, %	Bending MOE	Bending MOR
0	0.344	NA
20	0.545	0.093
30	0.000	0.031
40	0.285	0.476
50	0.000	0.000
60	0.000	0.000
All Filler Percentages	0.000	0.112

5.2 Tension

Tension tests were conducted to calculate the tensile MOE and the tensile strength for the wood-plastic composite panels. These properties were considered to be of primary importance and therefore, include a statistical analysis of the aged and unaged data. Test data consisted of load, extensometer displacement, and cross head movement.

In all cases, specimen failure occurred in the gage length area, examples are shown



Figure 5.9 – Tension Test Failures, top to bottom: 50% Wood Filler Content, 0%, and 30%. Note three marks designate measured cross sections.

in Figure 5.9. Three cross section measurements were taken in the gage length area of the specimen prior to testing. Two measurements were at the end of the gage length and one at the midpoint. The dimension closest to the failure was used for calculation purposes. The fracture surface typically revealed protruding wood fibers or large pieces of plastic that bonded poorly as shown in Figure 5.10. Some 0% wood filler content specimens could not be held firmly in the grips and, thus, could not be tested.

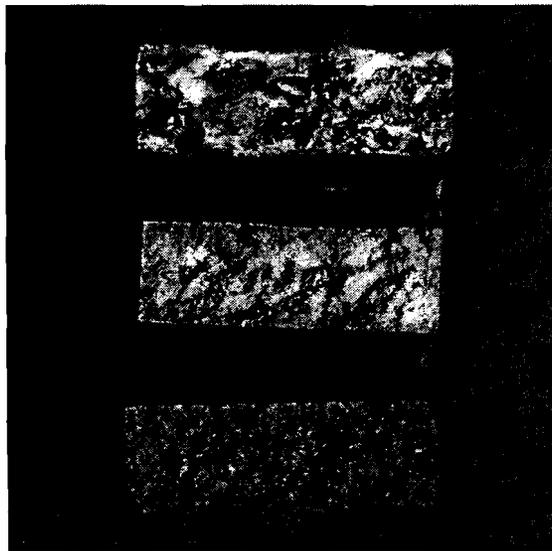


Figure 5.10 – Cross Sections of Tension Test Failures, top to bottom: 0% Wood Filler Content, 30%, and 50%.

The initial slope of the load verses strain curve for the tension specimens was calculated by the Testworks® program (see Appendix D). Some randomly selected slope values were checked using a nonlinear fit program to insure accuracy. The slope of every curve was visually inspected to insure a reasonable fit to the load verses displacement curve. Slope values were converted to tensile MOE values using the following equations. The variable σ_T is the tensile stress, $P = \text{Load}$, and $A = \text{cross sectional area at the failure}$.

$$\sigma_T = \frac{P}{A} \quad (5.10)$$

Material strain, ε , where $L = \text{gage length}$ and $\Delta = \text{extensiometer deflection}$

$$\varepsilon = \frac{\Delta}{L} \quad (5.11)$$

MOE is equal to the slope of the stress vs. strain curve, or

$$MOE = \frac{d\sigma}{d\varepsilon} \quad (5.12)$$

Substituting Equations 5.10-5.12 gives

$$MOE = \frac{L}{A} \cdot \frac{dP}{d\Delta} \quad (5.13)$$

In this case, the gage length term, L , is equal to one inch, so the tensile MOE can be calculated by dividing the slope of the load verses displacement curve by the cross sectional area. Figure 5.11 shows the tensile MOE values for standard and aged specimens and Table 5.4 summarizes the results.

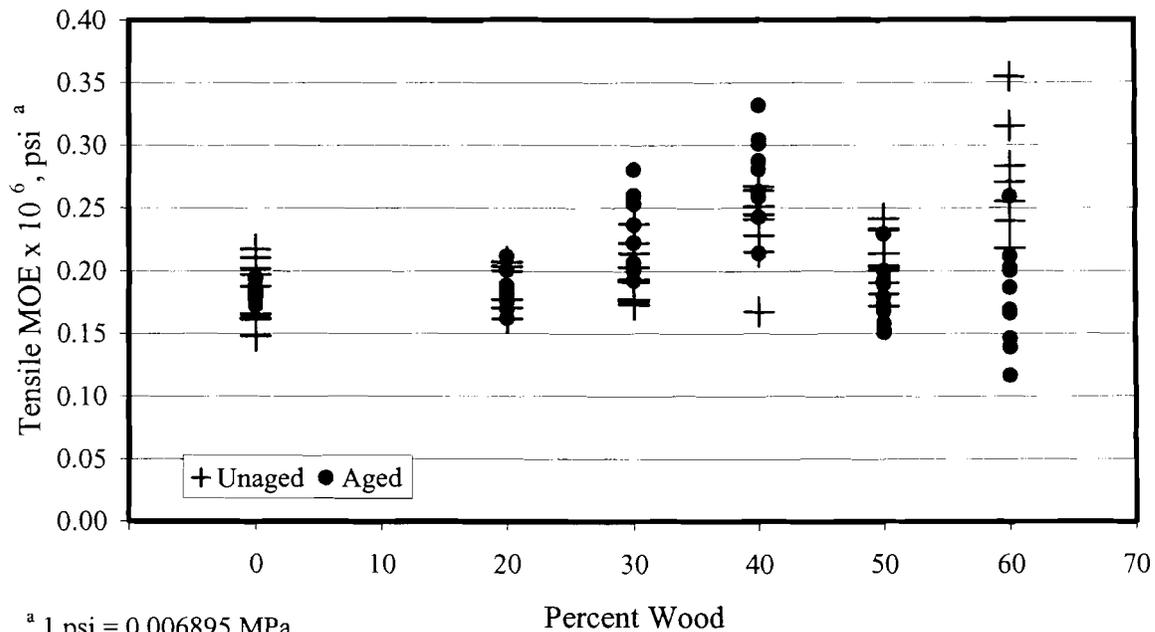


Figure 5.11 - Tensile Modulus of Elasticity Comparison of Aged and Unaged Specimens

Table 5.4 - Summary of Tensile MOE Test Results

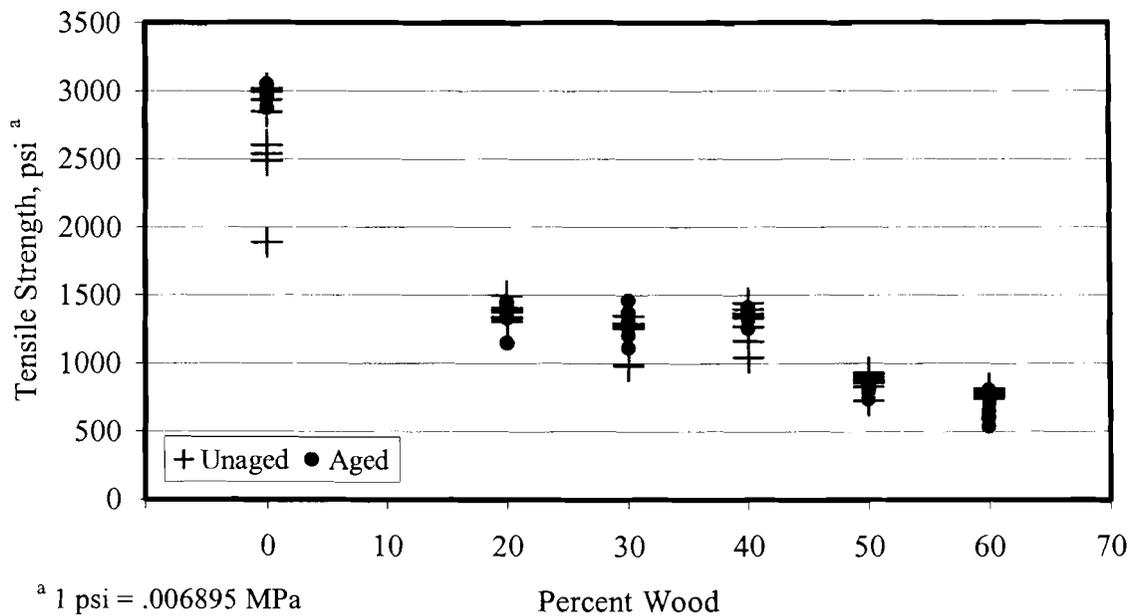
Percent Wood Flour	Unaged Specimens			Aged Specimens		
	n ^b	Mean MOE, psi x 10 ⁶ (MPa)	COV ^a	n ^b	Mean MOE, psi x 10 ⁶ (MPa)	COV ^a
0	10	0.18 (1240)	0.13	10	.18 (1240)	0.05
20	9 ^c	0.19 (1310)	0.09	10	.18 (1240)	0.08
30	9 ^c	0.20 (1380)	0.11	10	.23 (1590)	0.13
40	9	0.24 (1650)	0.13	9 ^c	.28 (1930)	0.13
50	10	0.21 (1450)	0.11	10	.18 (1240)	0.14
60	9 ^c	0.29 (2000)	0.18	10	.18 (1240)	0.23

a Coefficient of Variation

b Number of specimens used to calculate results

c Material flaw found in unreported specimens

The tensile strength (peak tensile stress) was calculated by substituting the maximum load for P in Equation 5.10. Figure 5.12 shows the peak tensile stress and Table 5.5 summarizes the tension test results for peak stress. Figure 5.13 graphically shows the



**Figure 5.12 - Tensile Strength
Comparison of Aged and Unaged Specimens**

Table 5.5 - Summary of Tensile Strength Results

Percent Wood Flour	Unaged Specimens			Aged Specimens		
	n ^b	Mean Strength, psi (MPa)	COV ^a	n ^b	Mean Strength, psi (MPa)	COV ^a
0	10	2730 (18.8)	0.13	10	2970 (20.5)	0.02
20	9 ^c	1380 (9.5)	0.04	10	1370 (9.4)	0.06
30	9 ^c	1250 (8.6)	0.08	10	1290 (8.9)	0.07
40	9 ^c	1310 (9.0)	0.10	9 ^c	1360 (9.4)	0.04
50	10	870 (6.0)	0.07	10	840 (5.8)	0.06
60	9 ^c	780 (5.4)	0.04	10	690 (4.8)	0.13

^a Coefficient of Variation

^b Number of specimens used to calculate results

^c Material flaw found in unreported specimens

result of the accelerated aging procedure for the tensile MOE and the peak tensile stress.

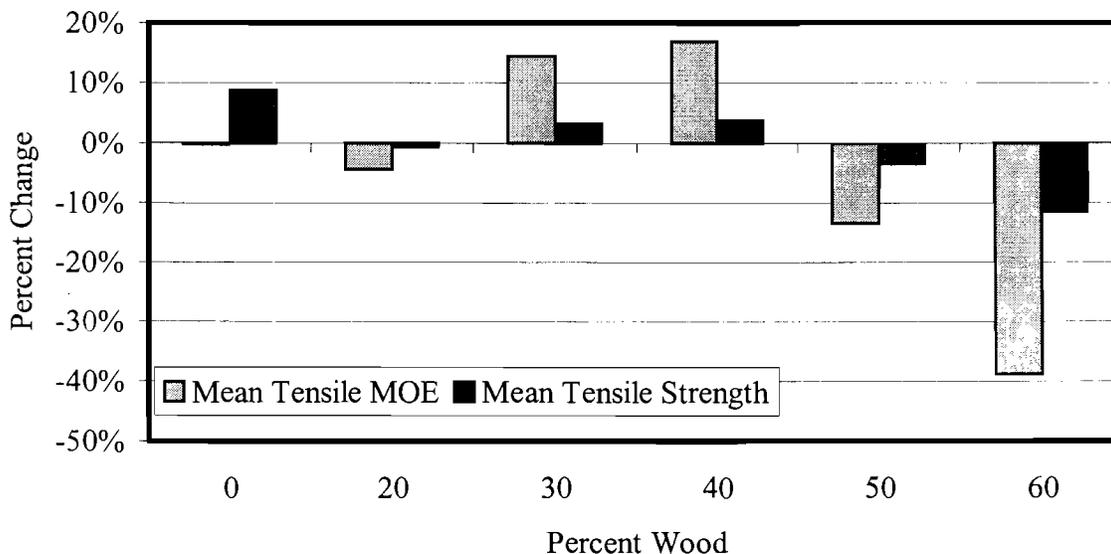


Figure 5.13 - Percent Change in Mean Tension Results Due to Accelerated Aging Exposure

Tensile MOE values were not as consistent as the tensile strength results. There was a general trend of an increasing MOE with wood percentage (61% change in tensile MOE ranging from 0% to 60% wood filler content), but an equation could not be defined with a acceptable fit (see Figure 5.14). The 50% wood specimens exhibited a low tensile MOE possibly due to the previously described material flaw.

Changes in the tensile MOE due to accelerated aging were not consistent enough to establish a defined outcome from aging. Table 5.6 shows the probability of the unaged and aged means being equal using a two-tailed t-test. It appears that the tensile MOE values are significantly different for panels with a filler percentage greater than 20% wood filler content. The resulting changes were not conclusive enough to substantiate the aging effects on the tensile MOE, but a substantial decrease in MOE resulted above the 40% specimens.

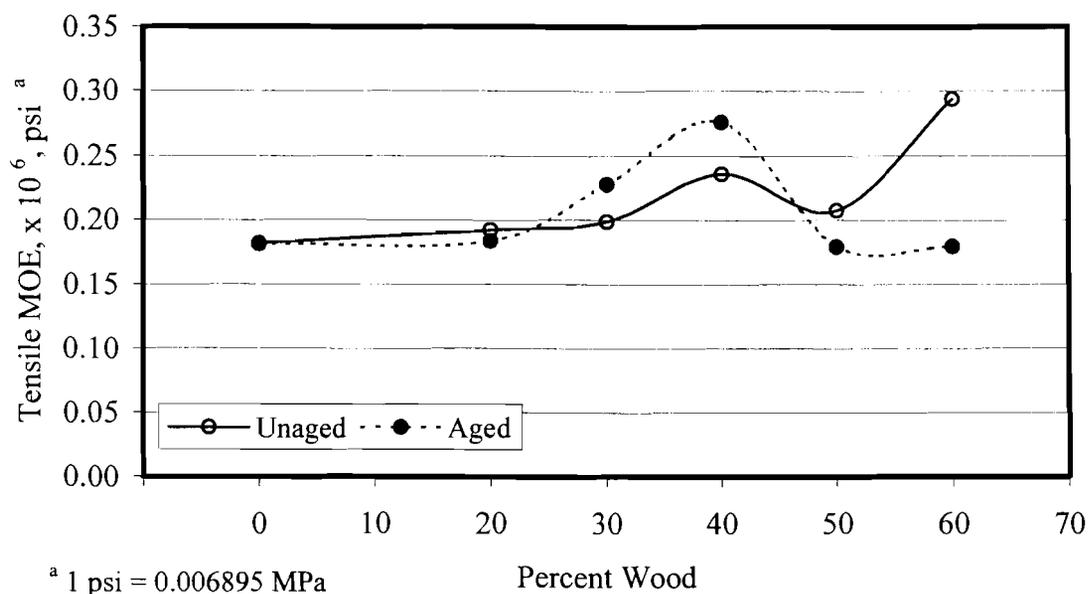


Figure 5.14 - Trends in the Mean Tensile Modulus of Elasticity

Table 5.6 – T-test P-values of Equal Means for Aged and Unaged Tension Data

Wood Flour, %	Tensile MOE	Tensile Strength
0	0.953	0.053
20	0.260	0.647
30	0.028	0.396
40	0.020	0.268
50	0.017	0.299
60	0.000	0.012
All Filler Percentages	0.104	0.885

Tensile strength of wood-plastic panels is directly affected by wood filler content. The strength values decreased by 71% for unaged specimens comparing 0% to 60% wood filler content. Similar to the bending MOR, the decrease in tensile strength can be attributed to additional fracture sites caused by adding wood fibers. Figure 5.15 shows a linear fit for peak tensile stress in unaged specimens found using least squares (Devore, 1995). The high strength values in the 0% wood specimens may be attributed to the

difference in thermoplastic resin types and therefore was not included with the fit data.

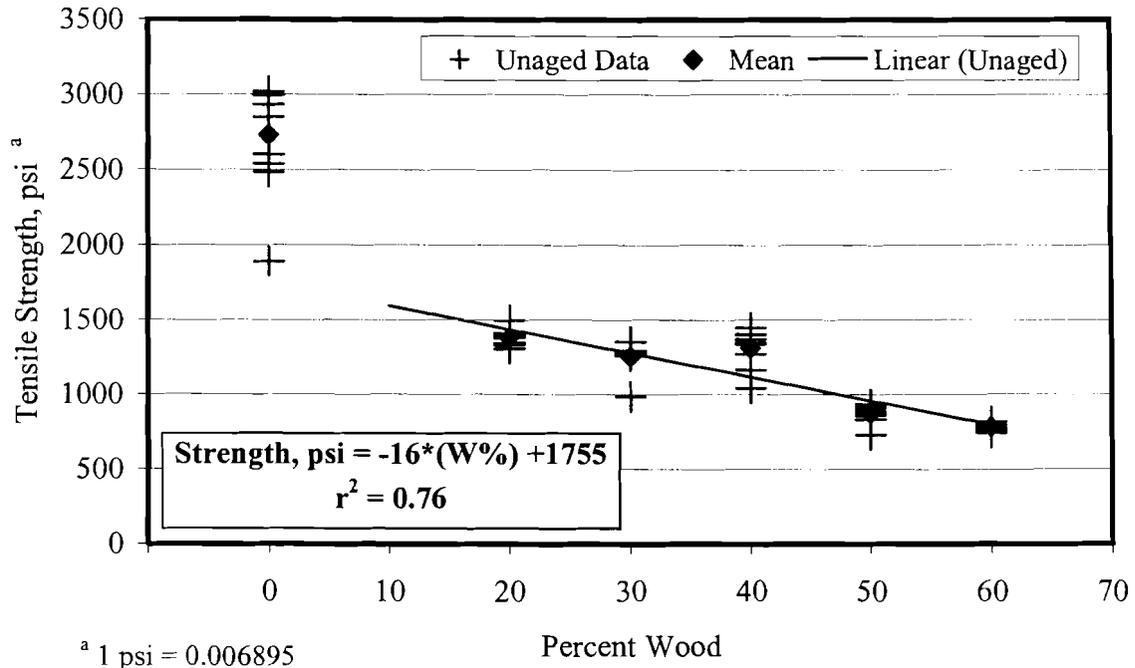


Figure 5.15 - Linear Fit for Tensile Strength, 0% Wood Filler not Included in Data Set Used for Linear Regression.

Accelerated aging did not appear to have a great impact on tensile strength as shown in Figure 5.16 and Table 5.6. The individual panel groups were above the range for accepting the null hypothesis of equal means in the majority of the wood flour percentages. The P-value comparing the means for the entire aged and unaged data sets was very high. This concludes that if additional specimens were tested, all panel percentage group would have equal unaged and aged means.

For tensile loads, the entire cross section resists the tensile force transmitted through the specimen. If the aging process does not diminish the interior material strength, the peak stress should not be affected, hence maintaining tensile strength.

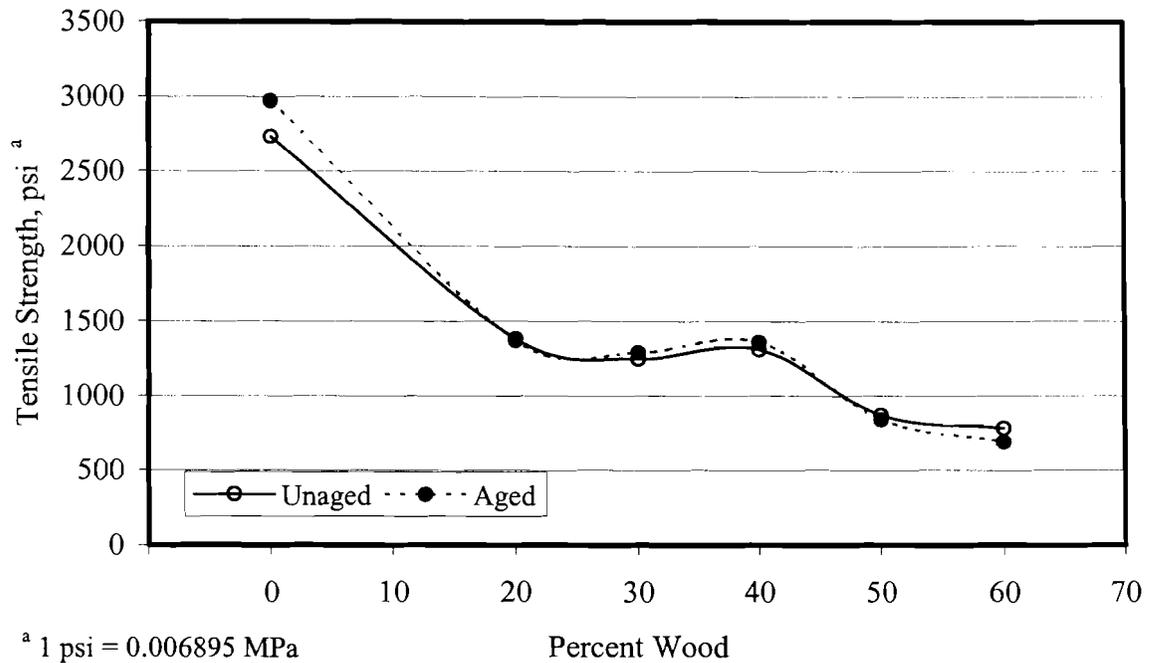


Figure 5.16 - Trends in the Mean Tensile Strength

5.3 Edgewise Shear

Edgewise shear tests were performed to find the shear strength for wood-plastic panel products. Shear strength was considered to be of primary importance and therefore, statistical analysis of the aged and unaged data was performed. Test data consisted of load values and crosshead displacement as shown in Appendix A.

Figure 5.17 displays the specimen failure typically was distributed throughout the length of the panel. Cracks formed on a 45 degree angle relative to the load direction. Specimens also failed at the rail/specimen interface at the blunt end of both rails. These cracks developed before the shear cracking and can be see in Figure 5.17. These cracks suggest that the specimen was under flexural stresses imposed from the cantilevered effect the rails created. The maximum moment in a cantilevered beam occurs at the support as

shown here. All four corners of the specimen showed large amounts of rotation in the rail gripping area.



Figure 5.17 – Edgewise Shear Failure. Note diagonal cracking.

Deformations in the 0% wood filler specimens were too large to be accommodated in the test setup. The top and bottom of the sample contacted the edges of the V notched fixtures causing incorrect load values. Some specimens slipped in the loading rails during testing resulting in local failures at the bolt holes.

The edgewise shear strength was calculated using the following equation

$$f_s = \frac{P_c}{L \cdot t} \quad (5.15)$$

where P_c equals the maximum compressive force, L is the panel length, and t is the specimen thickness (ASTM, 1992). The shear strength data is shown in Figure 5.18.

Tabular values of the average, effect of the accelerated aging, number of specimens used for calculating the results, and the coefficient of variation for each wood percentage can be found in Table 5.7.

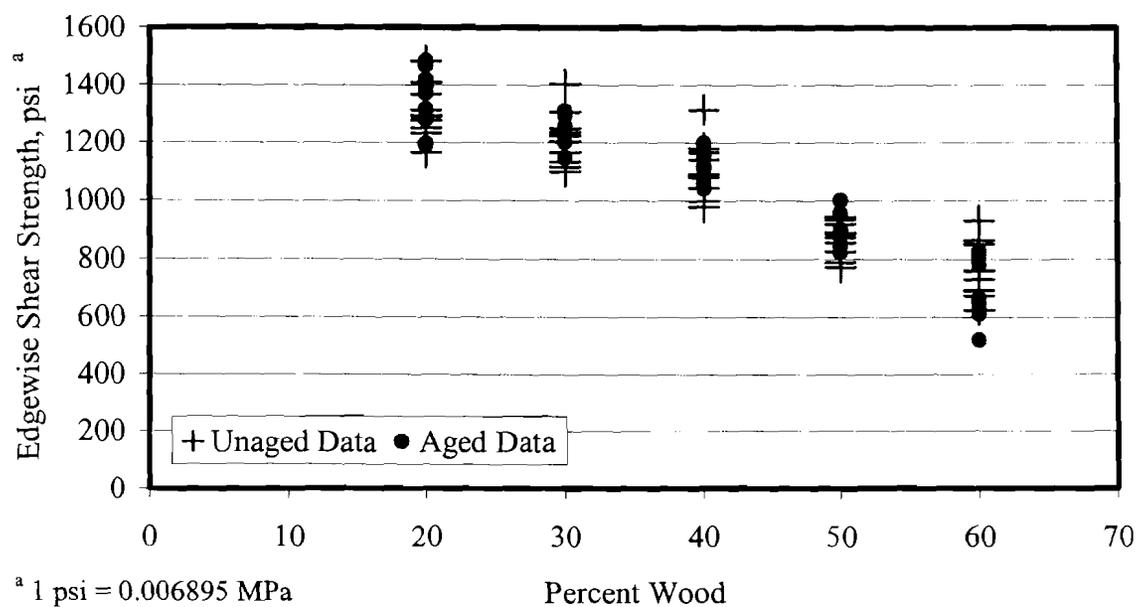


Figure 5.18 - Edgewise Shear Strength Comparison for Aged and Unaged Specimens

Table 5.7 - Summary of Edgewise Shear Strength Test Results

Percent Wood Flour	Unaged Specimens			Aged Specimens			Percent Change due to Aging
	n ^b	Shear Strength, psi (MPa)	COV ^a	n ^b	Shear Strength, psi (MPa)	COV ^a	
0	0	NA ^d	NA	0	NA ^d	NA	NA
20	10	1310 (9.0)	0.07	10	1350 (9.3)	0.08	3.5
30	10	1210 (8.3)	0.08	8 ^c	1240 (8.5)	0.04	2.1
40	10	1110 (7.7)	0.09	10	1110 (7.7)	0.04	-0.2
50	10	870 (6.0)	0.07	10	900 (6.2)	0.06	4.0
60	10	760 (5.2)	0.13	10	710 (4.9)	0.16	-5.9

^a Coefficient of Variation

^b Number of specimens used to calculate results

^c Slippage in grips for unreported specimens

^d Material strain was in excess of what mechanical testing equipment allowed

The wood filler content ratio effected the edgewise shear strength in tests conducted on wood-plastic composite panels. The mean shear strength for the 60% wood content was

about 42% lower than for the 20% wood content specimens. This decrease in strength is represented linearly by the equation shown in Figure 5.19. The fit was computed using a least squares fit of the unaged data (Devore, 1995).

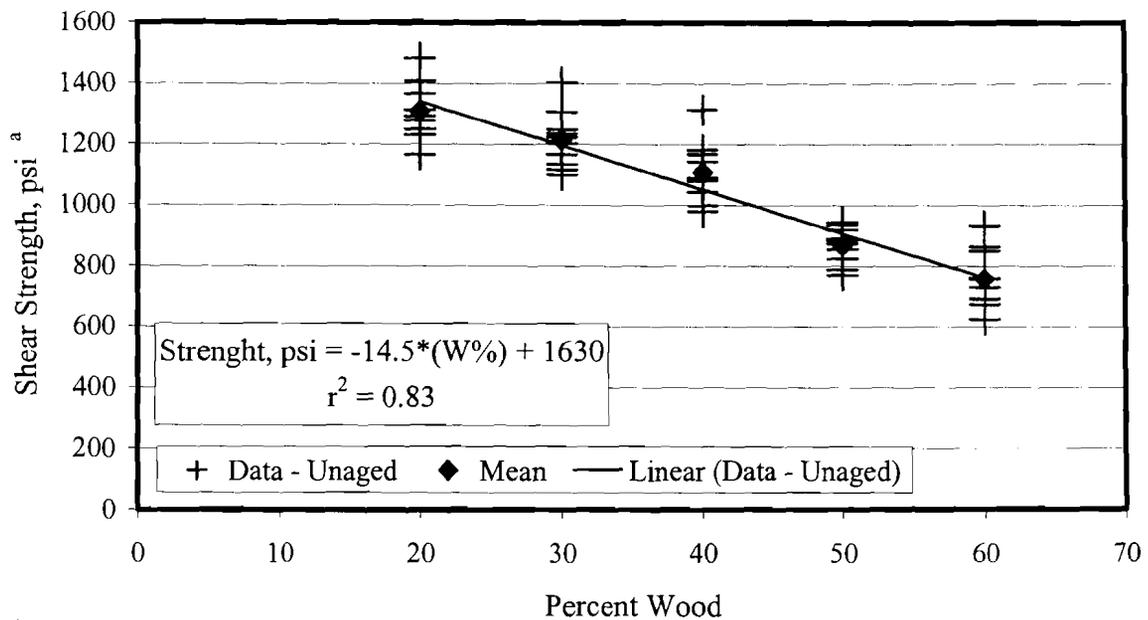


Figure 5.19 - Linear Fit of Unaged Edgewise Shear Strength Data

Shear failures occurred on a 45° angle from the load direction coinciding with the maximum tensile shear line as shown in Figure 5.20. This observation coincides with trends in solid wood products, that is, failures in wood-plastic composites typically originate from tensile forces. As more wood flour is added to the material, more voids are created in the base plastic material. These voids weaken the material and hence lower peak stress values result.

The statistical analysis of the unaged and aged data is shown in Table 5.8. The P-values for all test groups were above the acceptable significance level concluding that accelerated aging exposure did not significantly effect shear strength as confirmed in Figure

5.21. The high P-value for all filler percentages suggests that additional test data would increase the significance level of equal means in all test groups. The greatest change in the mean peak shear stress due to aging was 6%.

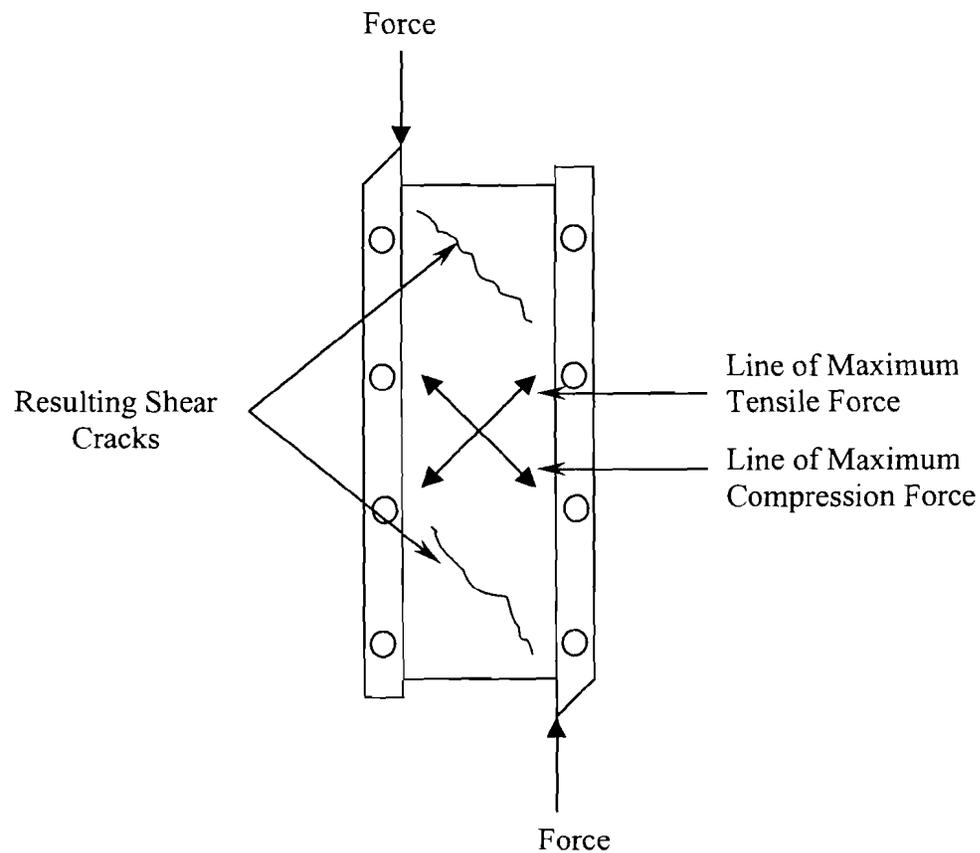


Figure 5.20 – Resulting Edgewise Shear Forces. Note shear cracks and lines of maximum tensile and compressive forces.

Table 5.8 – T-test P-Values of Equal Means for Aged and Unaged Shear Data

Wood Flour, %	Edgewise Shear Strength
20	0.318
30	0.491
40	0.944
50	0.186
60	0.348
All Filler Percentages	0.928

A panel resists shear force throughout the thickness of the material. If the aging

process did not penetrate through the entire cross section of the sample, the shear resistance of the material should not drastically change. Results from the bending test showed decreases in property values after exposure to aging. Since the material resistance to bending stress is greatest at the extreme fiber, it is logical to assume that any material degradation at the outer surface will effect a material's bending performance. Conversely, if the material resistance is greatest at the panel core, accelerated aging is not as likely to alter the property.



Figure 5.21 - Trends in Mean Peak Edgewise Shear Strength Comparing Aged and Unaged Values.

5.4 Hardness

Hardness tests were conducted to determine the load associated with the displacement of a modified Janka Ball (see Section 4.4). Crosshead displacement values were also recorded to be used in calculating the hardness modulus. The hardness modulus is the slope of the load versus displacement curve. It is often used as an alternate method

for finding the hardness of a material to avoid using a one inch thick specimen. Similar to the tension test, slope values were calculated with the Testworks® program, visually inspected, and randomly checked with the nonlinear curve fit. All of the computed slopes matched the original values generated by Testworks®.

The material deformation was uniform in the top layer of the specimen. The deformation did not translate to the lower portion of the specimen. There was no cracking failure evident throughout the cross section.

The test results for hardness load results are shown Figure 5.22 and tabular test summary values are shown in Table 5.9. The hardness modulus values are displayed in Figure 5.23 for both aged and unaged specimens. Tabulated results are shown in Table 5.10 and the effect of the accelerated aging procedure is graphically displayed for both hardness load and hardness modulus in Figure 5.24.

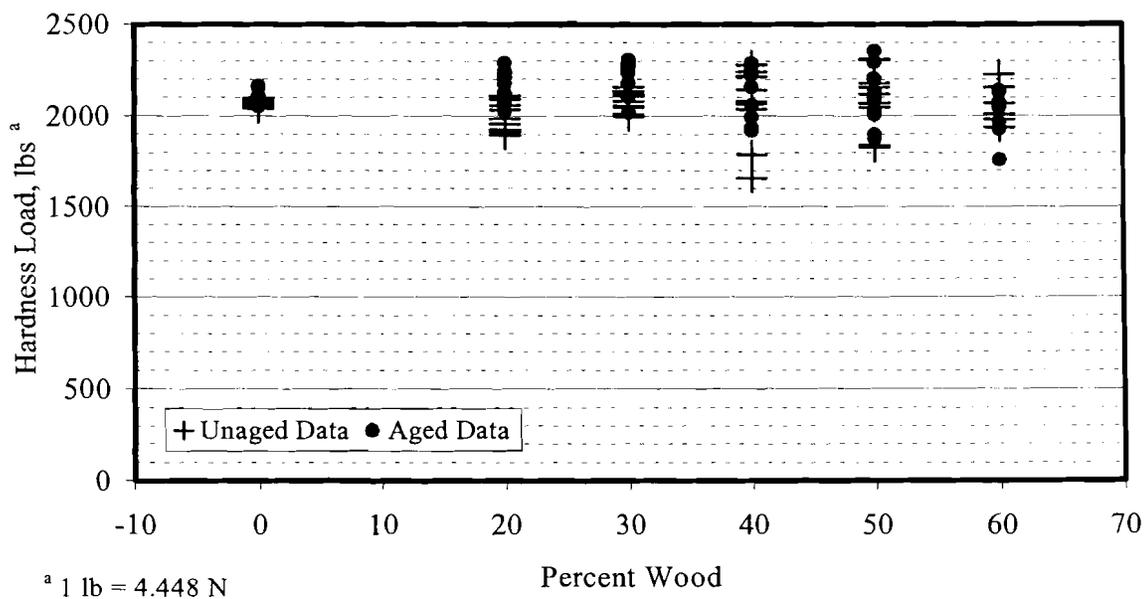


Figure 5.22 - Hardness Load Comparison for Aged to Unaged Specimens

Table 5.9 – Summary of Hardness Load Test Results

Percent Wood Flour	Unaged Specimens			Aged Specimens		
	n ^b	Mean Hardness Load, lbs (N)	COV ^a	n ^b	Mean Hardness Load, lbs (N)	COV ^a
0	10	2070 (9210)	0.01	9 ^d	2120 (9430)	0.02
20	10	2000 (8900)	0.04	10	2170 (9650)	0.04
30	10	2080 (9250)	0.03	10	2210 (9830)	0.04
40	10	2080 (9250)	0.10	10	2130 (9470)	0.07
50	9 ^c	2090 (9300)	0.08	9 ^c	2100 (9340)	0.08
60	8 ^d	2060 (9160)	0.05	8 ^d	2010 (8940)	0.06

a Coefficient of Variation
 b Number of specimens used to calculate results
 c Material flaw in unreported specimens
 d Shortage of specimens for testing

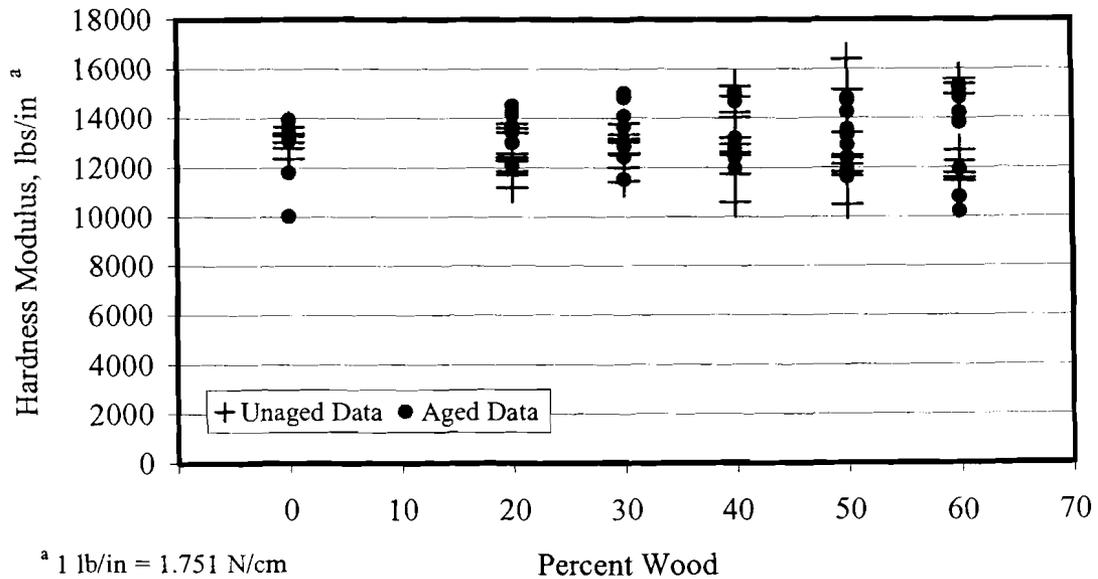


Figure 5.23 - Hardness Modulus Comparison for Aged and Unaged Specimens

Table 5.10 - Summary of Hardness Modulus Test Results

Percent Wood Flour	Unaged Specimens			Aged Specimens		
	n ^b	Mean Hardness Modulus, lbs (N)	COV ^a	n ^b	Mean Hardness Modulus, lbs (N)	COV ^a
0	10	13100 (22900)	0.03	9 ^d	12900 (22600)	0.10
20	9 ^d	12500 (21900)	0.07	10	13600 (23800)	0.05
30	10	12800 (22400)	0.05	10	13500 (23600)	0.09
40	10	13200 (23100)	0.11	10	13800 (24200)	0.09
50	9 ^c	12900 (22600)	0.14	9 ^c	13300 (23300)	0.09
60	8 ^d	13200 (23100)	0.14	8 ^d	13300 (23300)	0.15

a Coefficient of Variation

b Number of specimens used to calculate results

c Material flaw in unreported specimens

d Shortage of specimens for testing

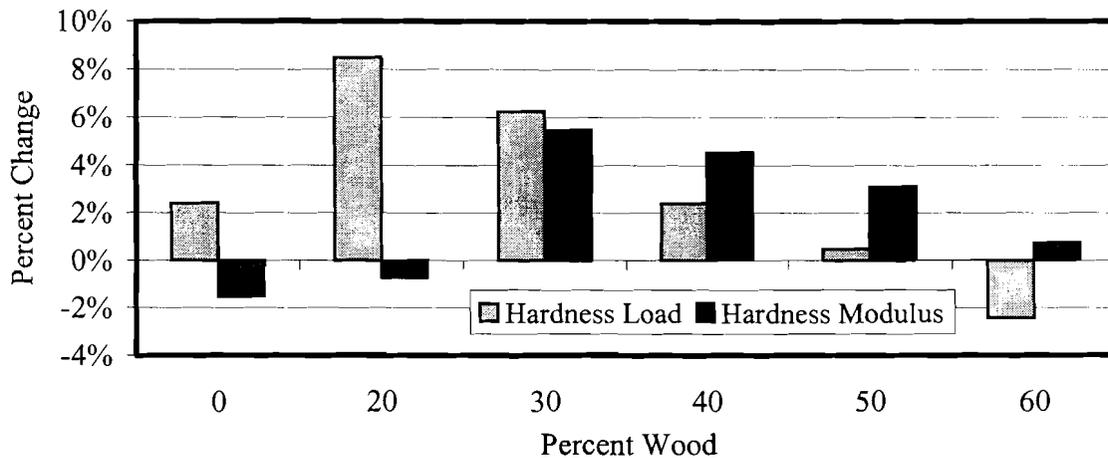


Figure 5.24 - Percent Change in Hardness Results Due to Accelerated Aging

Changing the wood percentage did not alter the measured hardness of all panel groups tested. All of the test values were slightly above 2000 pounds at .222 inches of penetration from the Janka Ball test. The material was under compressive forces during the

test. The voids accompanied with the addition of wood fibers may not effect the material's resistance to force as it did in the tension case. A constant line was used to represent the mean unaged hardness load data as shown in Figure 5.25. The equation was found by averaging the mean data from unaged hardness results.

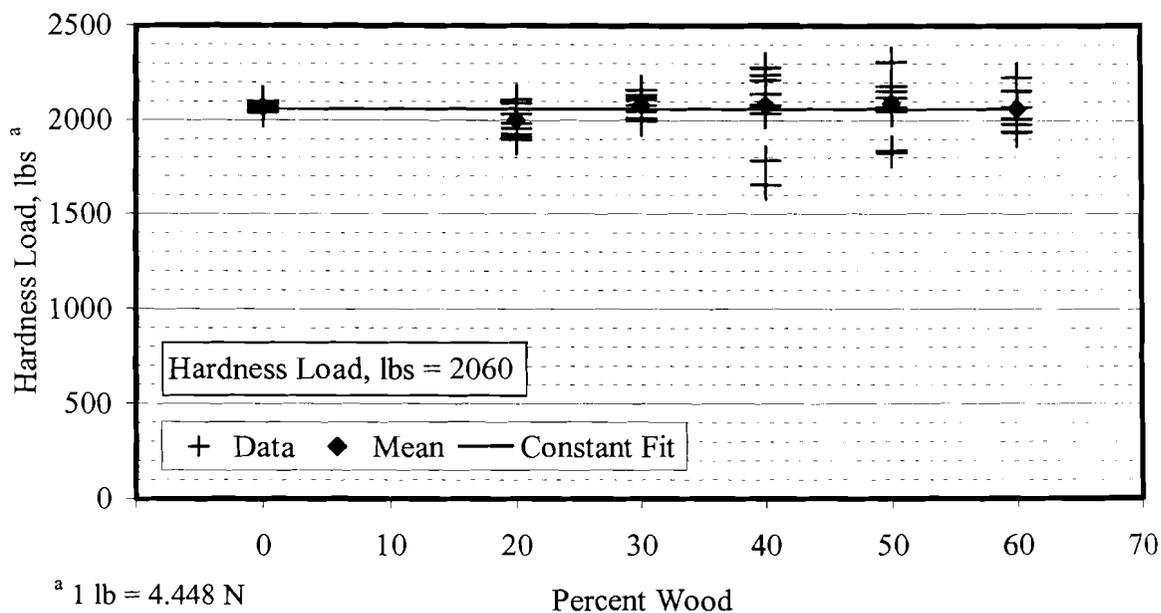


Figure 5.25 - Constant Fit for Unaged Hardness Load Data

The hardness modulus results were similar to hardness load values. Lewis has previously shown that there is a direct relationship between the hardness load and the hardness modulus (Lewis, 1968). A constant trend was also used to represent the hardness modulus values as shown in Figure 5.26. Typically, a constant is assigned to relate hardness and hardness modulus values. A factor of 6.4 results for wood-plastic composite panels using the equations previously described.

Accelerated aging did not have a significant effect on the hardness load. Figure 5.27 shows the mean values of both unaged and aged specimens for load and modulus. As found in the shear test, the material resistance against Janka Ball penetration is distributed

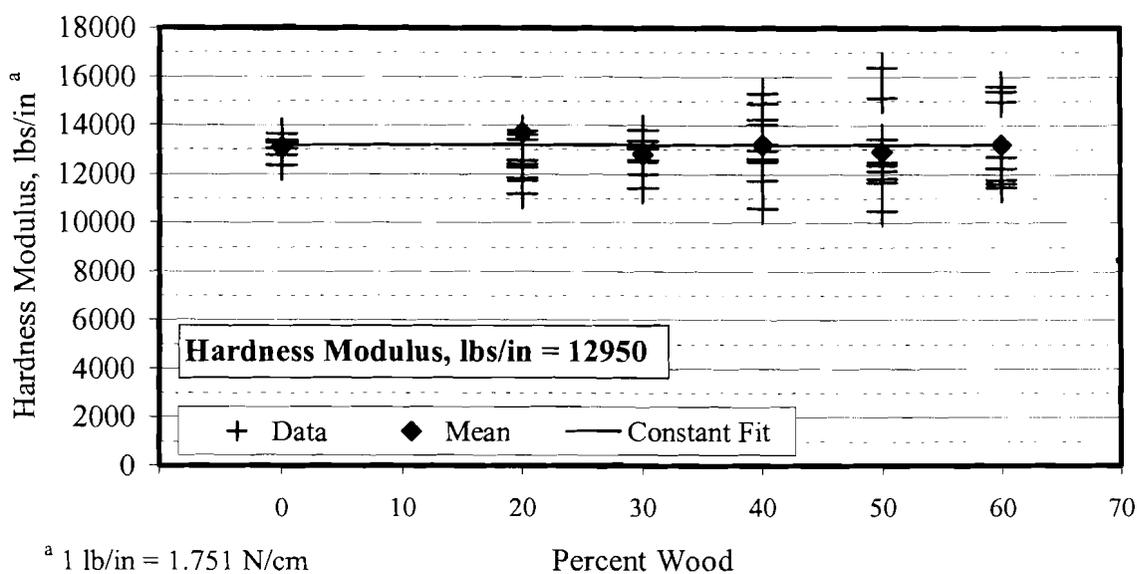


Figure 5.26 - Constant Fit for Unaged Hardness Modulus Data

throughout the specimen thickness. Since the aging exposure may have a limited penetration through the thermoplastic material, hardness load and modulus values are not drastically altered.

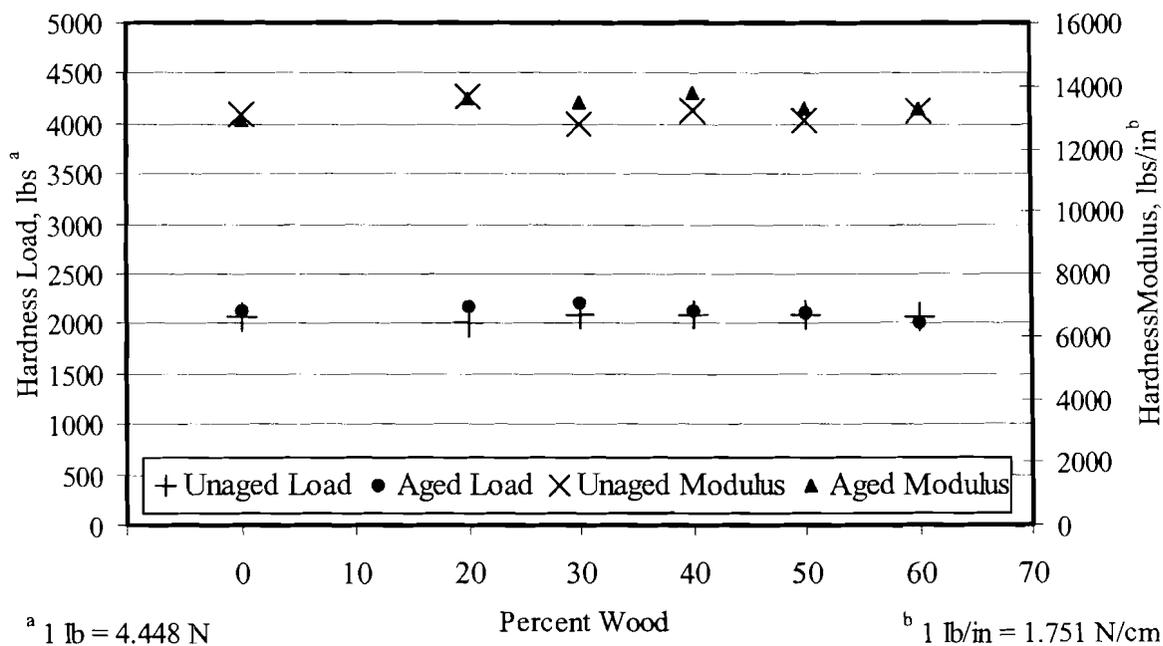


Figure 5.27 - Mean Hardness Load and Hardness Modulus Trends

5.5 Moisture Absorption

Tests were performed to determine the effects of moisture on wood-plastic composite panels. Volume and weight of the specimens were monitored to quantify moisture absorption characteristics of the panels. The physical property changes are expressed as a percentage of the original values for volume and weight. The 24-hour changes are included in Figures 5.28 and 5.29. Tables 5.11 and 5.12 summarize the moisture test results for volume and weight, respectively.

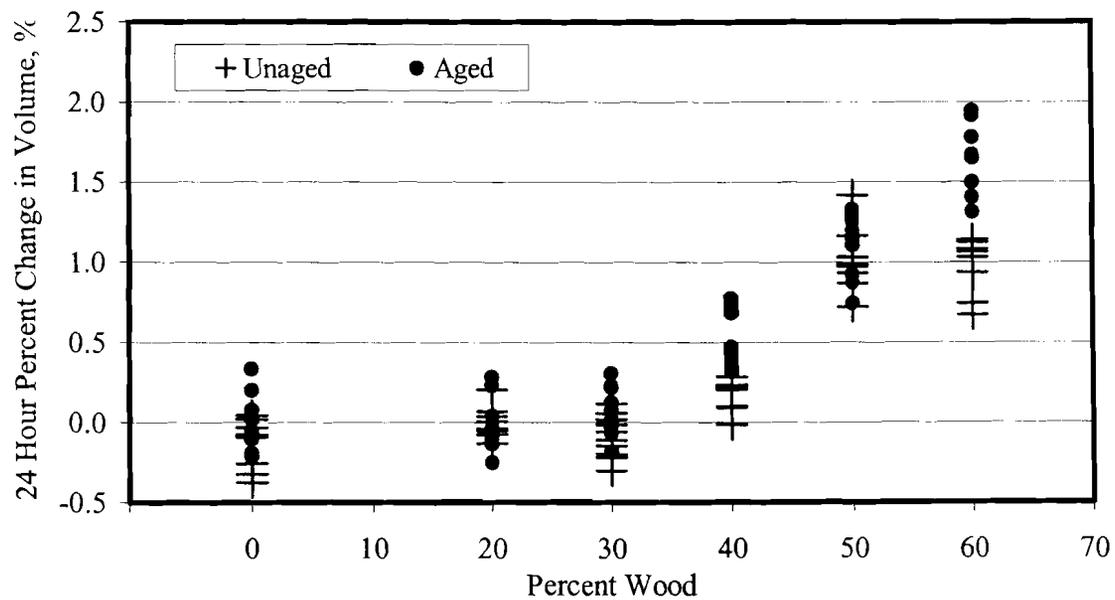


Figure 5.28 - Percent Change in Volume due to the 24-Hour Moisture Absorption Test.

Table 5.11 - Summary of the 24-Hour Moisture Absorption Test Results for Change in Volume.

Percent Wood Flour	Unaged Specimens			Aged Specimens		
	n ^b	Mean 24 Hour Percent Change in Volume	s ^a	n ^b	Mean 24 Hour Percent Change in Volume	s ^a
0	10	-0.13	0.14	10	-0.01	0.17
20	10	0.00	0.09	10	-0.02	0.16
30	10	-0.09	0.13	10	0.07	0.12
40	10	0.16	0.11	10	0.57	0.18
50	10	1.01	0.18	10	1.12	0.20
60	9 ^c	0.99	0.17	9 ^c	1.66	0.22

a Standard Deviation

b Number of specimens used to calculate results

c Shortage of specimens for testing

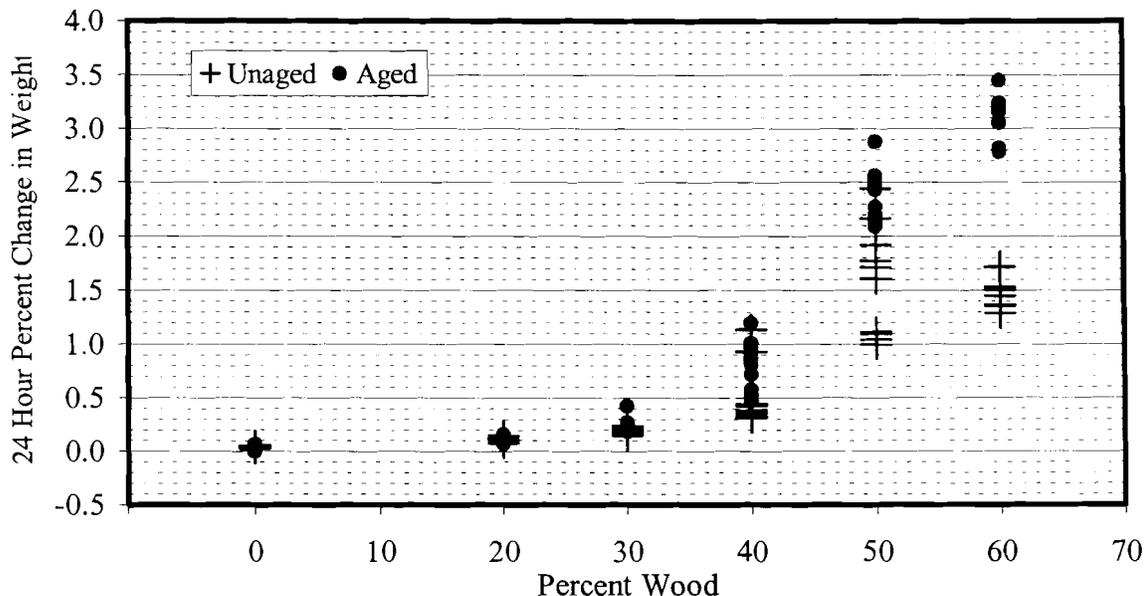


Figure 5.29 - Percent Change in Weight Resulting from the 24-Hour Moisture Absorption Test.

Table 5.12 - Summary of the Percent Change in Weight Resulting from the 24-Hour Moisture Absorption Test.

Percent Wood Flour	Unaged Specimens			Aged Specimens		
	n ^b	Mean 24 Hour Percent Change in Weight	s ^a	n ^b	Mean 24 Hour Percent Change in Weight	s ^a
0	10	0.04	0.01	10	0.02	0.02
20	10	0.12	0.02	10	0.12	0.02
30	10	0.19	0.03	10	0.25	0.07
40	10	0.51	0.28	10	0.80	0.23
50	10	1.58	0.51	10	2.37	0.24
60	9 ^c	1.45	0.13	9 ^c	3.10	0.21

a Standard Deviation

b Number of specimens used to calculate results

c Shortage of specimens for testing

The water absorption and material shrink/swell was found to be dependent upon the wood filler content. As the percentage of wood filler increased, the material began to behave less like the base moisture-resistant thermoplastic. The amount of water absorbed by the specimen was found to increase by 1.4% from 0% to 60% wood content for unaged specimens. The change in sample weight increased exponentially with the wood percentage as shown in Figure 5.30. Some of the 40% and 50% wood samples appeared to have irregularly high quantities of water absorption along with a relatively high coefficient of variation. This may be attributed to the forming complications associated with high wood filler content as described in the beginning of this chapter. The plane of poorly bonded pellets creates more air voids within the specimen. These voids allow more water infiltration resulting in an unproportional absorption value.

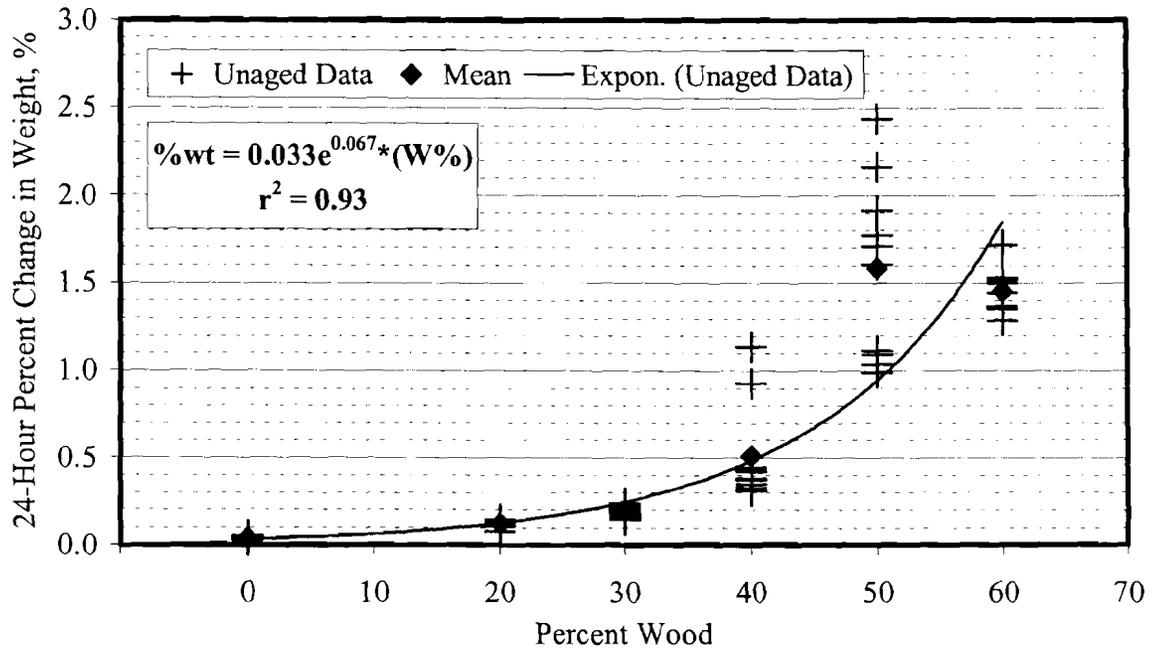


Figure 5.30 - Exponential Fit of the Percent Change in Weight for the 24-Hour Moisture Absorption Test

Results for the 24-hour change in volume could not be accurately described with an equation. Panels with low wood percentage (0% - 30%) yielded negative percent changes in mean volume after the 24-hour water soak. Higher wood percentage panels increased up to 1% of their original volume.

Aging had an influence on the mean percent change in volume as shown in Figure 5.31. Specimens with low percentages of wood did not change substantially while the high wood content samples increased .67% in volume for the 60% wood group. A possible explanation for the increased moisture absorption after aging is that the plastic outer surface layer was deteriorated. This protective layer did not allow as much water to get to the wood fibers. If the accelerated aging exposure compromised this layer, the wood filler became directly exposed to the water.

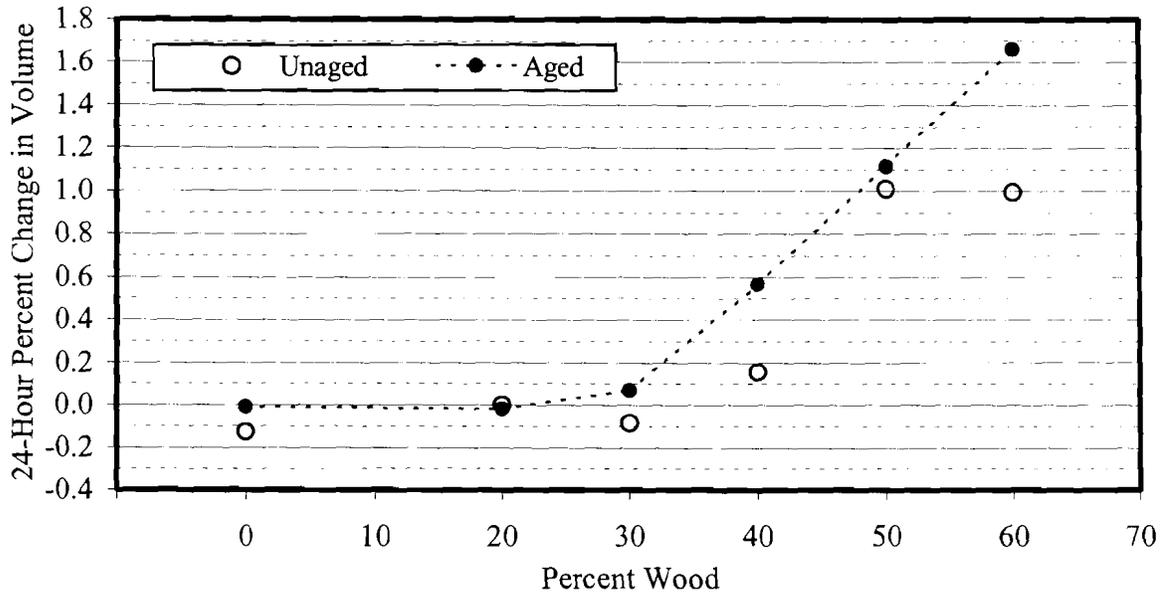


Figure 5.31 - Effect of Aging for the Mean Change in Volume from the 24-hour Moisture Absorption Test.

The accelerated aging exposure effected the panel’s moisture resistance in higher wood filler content panels as shown in Figure 5.32. The lower wood percentage panels (0%

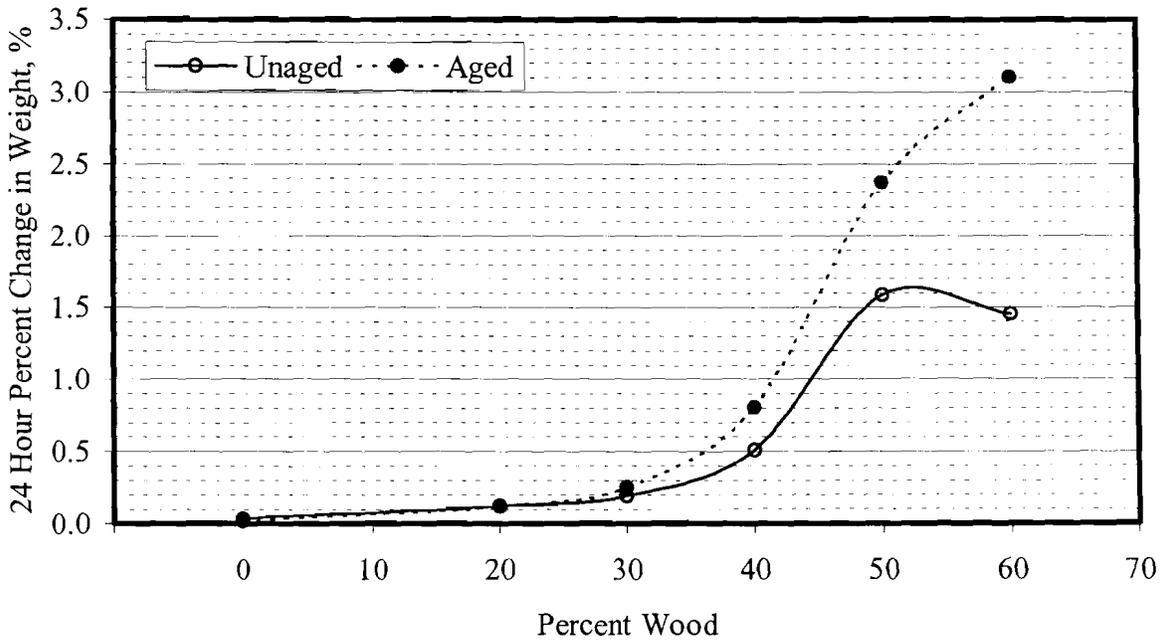


Figure 5.32 - Effect of Aging for the Mean Change in Weight Resulting from the 24-hour Moisture Absorption Test.

- 30%) did not change in water absorption after of the aging process. Conversely, the higher wood groups absorbed up to twice the amount of water than the matched set of unaged specimens.

Specific gravity and moisture content were also measured using the moisture absorption specimens. Results are shown in Figure 5.33 and Figure 5.34, respectively. The specific gravity, SG, was calculated using Equation 5.16 where F is the oven-dry sample weight, L equals length, w is the width, and t is the thickness of the sample (ASTM, 1992). Table 5.13 lists the summary data and average specific gravities for wood-plastic panels.

$$SG = 0.061 \cdot \frac{F}{Lwt} \quad (5.16)$$

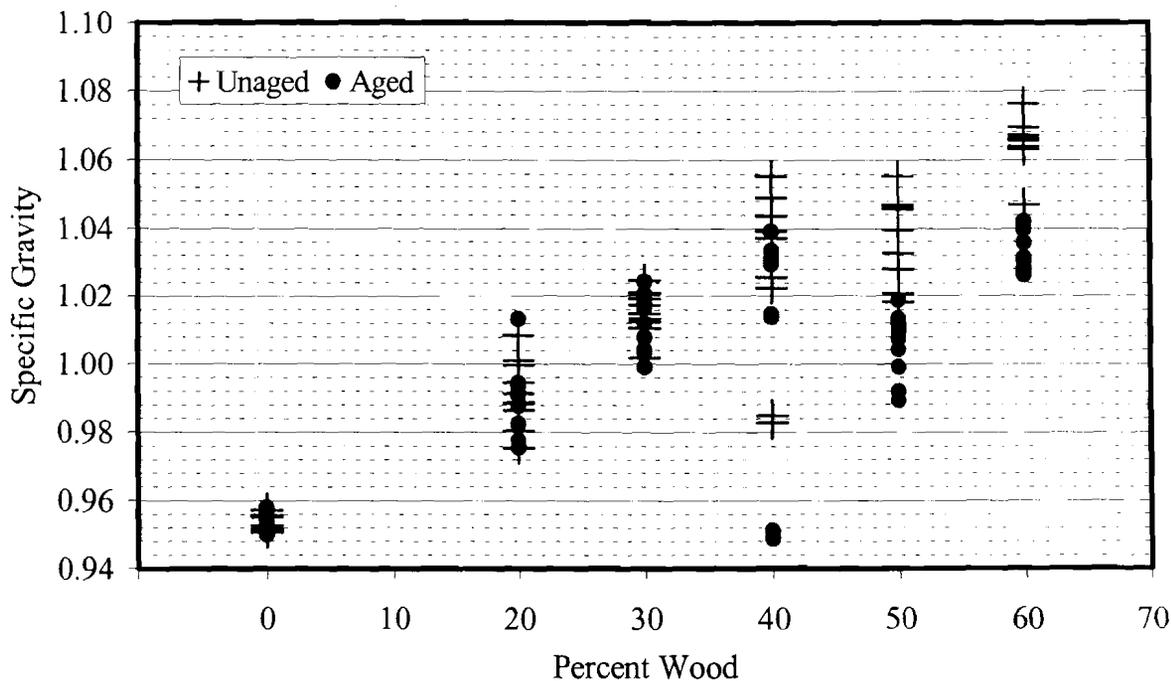


Figure 5.33 - Specific Gravity of Wood-Plastic Composite Panels

Table 5.13 – Mean Specific Gravity of Aged and Unaged Wood-Plastic Composites

Percent Wood Flour	Unaged Specimens			Aged Specimens		
	n ^b	Mean Specific Gravity	COV ^a	n ^b	Mean Specific Gravity	COV ^a
0	10	0.95	0.00	10	0.95	0.00
20	10	0.99	0.01	10	0.99	0.01
30	10	1.02	0.01	10	1.01	0.01
40	10	1.03	0.02	10	1.01	0.03
50	10	1.04	0.01	10	1.01	0.01
60	9 ^c	1.06	0.01	9 ^c	1.03	0.01

a Coefficient of Variation

b Number of specimens used to calculate results

c Shortage of specimens for testing

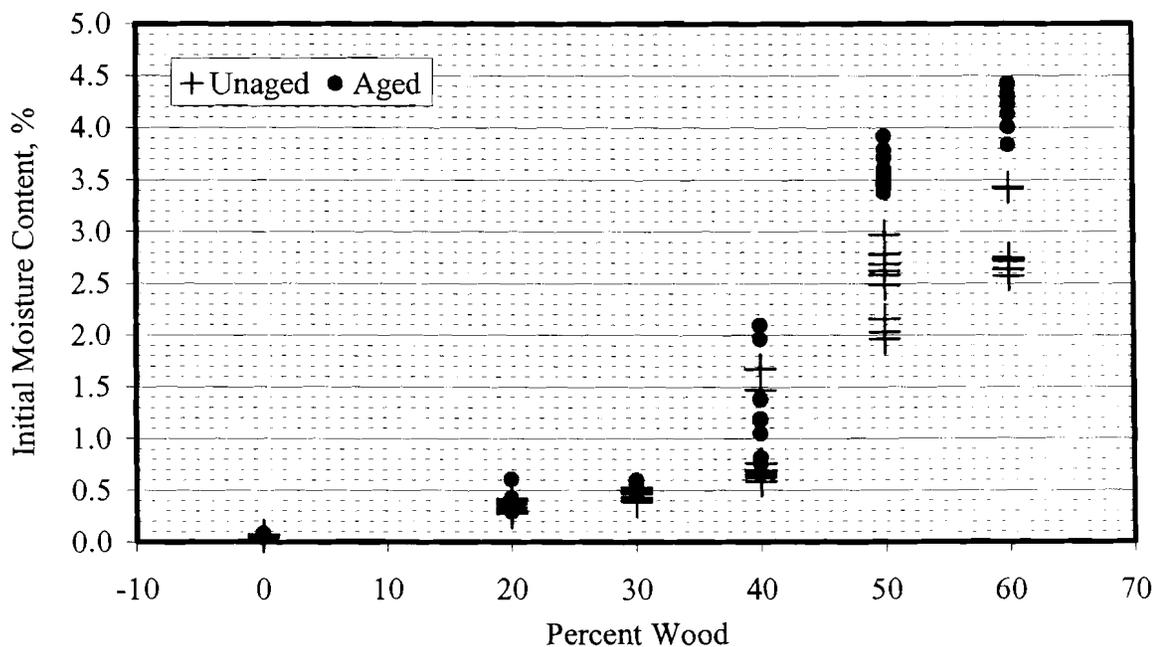


Figure 5.34 - Moisture Content at 65% Relative Humidity and 74 Degrees Fahrenheit

The moisture content, MC, of the panel specimens at 65% relative humidity was calculated as follows where W is the initial sample weight and F is the oven-dry weight (ASTM, 1992). The test summary values are shown in Table 5.14.

$$MC = 100 \cdot \frac{W - F}{F} \quad (5.17)$$

Table 5.14 – Mean Moisture Content of Aged and Unaged Wood-Plastic Composites at 65% Relative Humidity and 74°F.

Percent Wood Flour	Unaged Specimens			Aged Specimens		
	n ^b	Mean Moisture Content	COV ^a	n ^b	Mean Moisture Content	COV ^a
0	10	0.06	0.15	10	0.05	0.23
20	10	0.35	0.14	10	0.37	0.25
30	10	0.45	0.12	10	0.52	0.06
40	10	0.84	0.47	10	1.24	0.39
50	10	2.50	0.14	10	3.59	0.05
60	9 ^c	2.85	0.12	9 ^c	4.22	0.05

a Coefficient of Variation

b Number of specimens used to calculate results

c Shortage of specimens for testing

Specific gravity increased by 12% ranging from 0% to 60% wood filler content. A linear trend fit the unaged data using least squares as shown in Figure 5.35 (Devore, 1995). Considering that the specific gravity increased as wood flour was added, shows that the specific gravity of wood flour must be greater than the thermoplastic resin. Seasoned lumber usually has a specific gravity of about 0.5 - 0.6 and solid wood 1.45. Using Equation 5.18, the average specific gravity for wood flour equals 1.15. These results confirm previous statements about the specific gravity of wood fillers in Section 2.3

considering that glass fiber and calcium carbonate fillers possess specific gravities of 2.5 and 2.9, respectively.

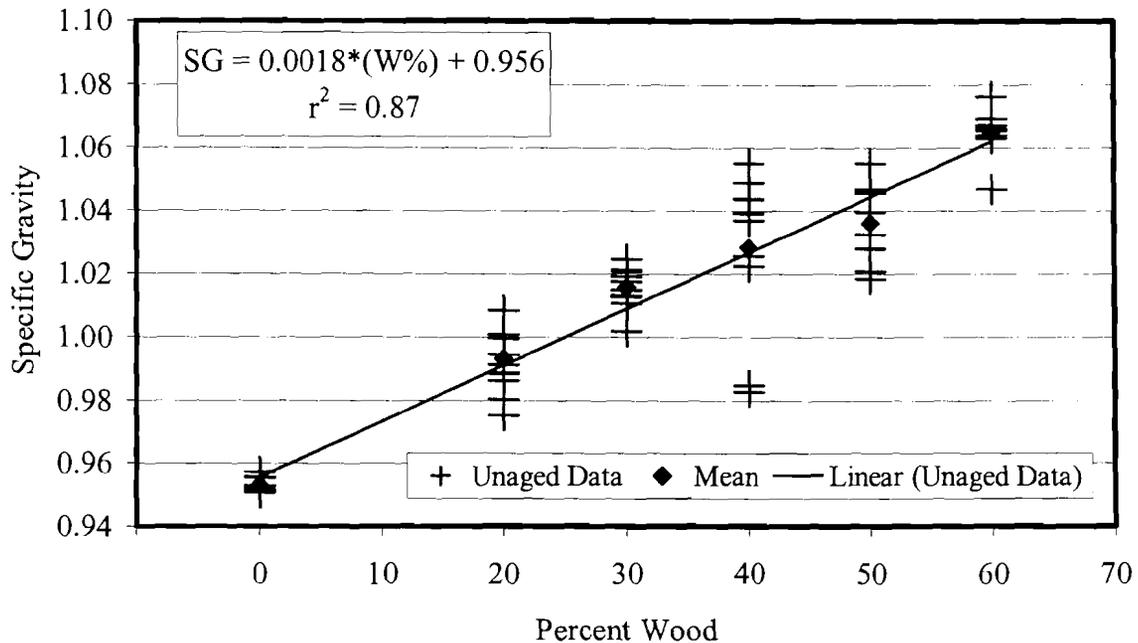


Figure 5.35 - Linear Fit for the Specific Gravity of Wood-Plastic Composite Panels

$$SG_{wf} = \frac{SG - (\%plastic \cdot .95)}{\%woodflour} \quad (5.18)$$

where

SG_{wf} = specific gravity of wood flour;

SG = specific gravity of the composite found from testing;

$\%plastic$ = thermoplastic content;

$\%woodflour = 1 - \%plastic$; and

0.95 is the mean specific gravity found for thermoplastic.

Accelerated aging did not drastically change the specific gravity. A 3% decrease was the largest change in mean specific gravity due to aging for 50% and 60% wood filler.

Moisture content increased by 2.8% in comparing 0% to 60% wood filler content.

An exponential fit to the unaged data was used to formulate an equation to describe the

change in the moisture content at standard conditions as shown in Figure 5.36.

Accelerated aging increased the moisture content by approximately 1.4% for the three highest wood percentage groups. Considering that specific gravity slightly decreased and moisture content increased after aging in high wood content samples, suggests that the aging process causes an increase in volume that created voids allowing additional moisture into the specimen.

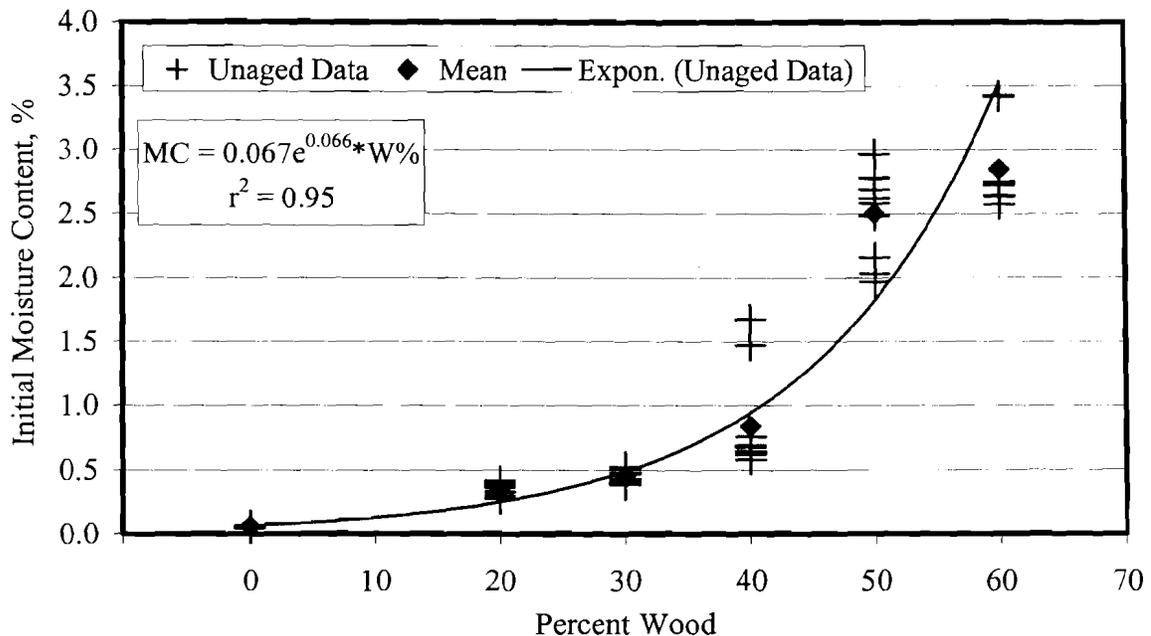


Figure 5.36 - Exponential Fit for Percent Change in Moisture Content with Wood Filler Content at 65% Relative Humidity and 74 Degrees Fahrenheit.

5.6 Thermal Expansion

The change in specimen length associated with temperature changes was used to calculate the coefficient of thermal expansion for wood-plastic composite panels. The coefficient of thermal expansion is the slope of the percent change in length vs. temperature

curve. This material property was considered to be of primary importance for wood-plastic panels and therefore, statistical analysis of the aged and unaged data was performed.

Figure 5.37 shows the calculated results of the data compiled in the testing procedure. Table 5.15 summarizes the mean results and the percent change due to accelerated aging.

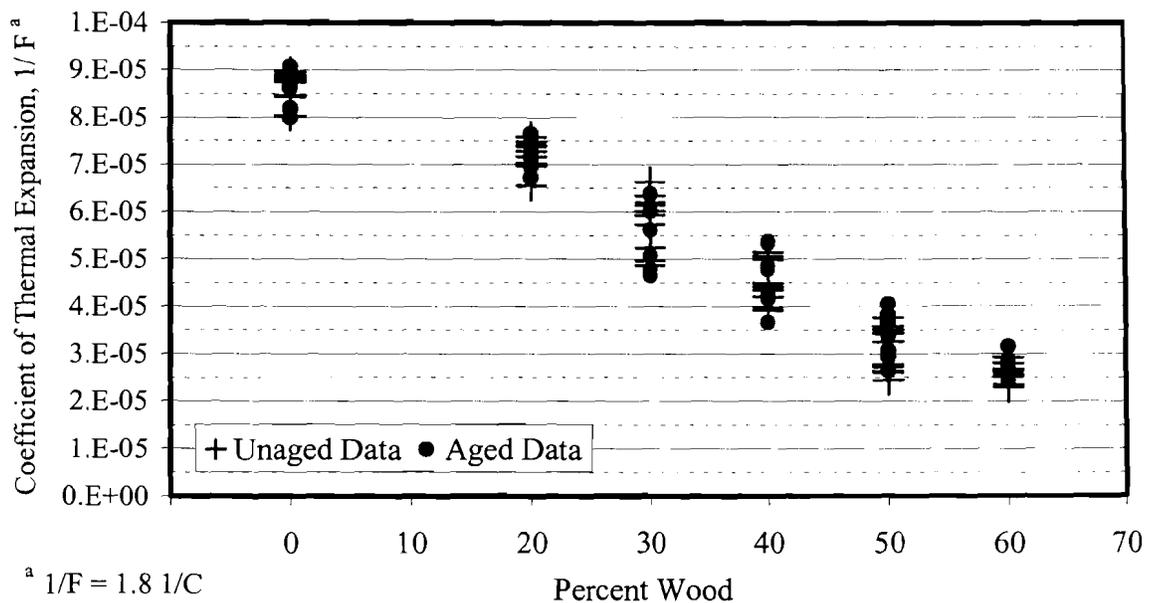


Figure 5.37 - Coefficient of Thermal Expansion Comparison for Aged to Unaged Specimens

The mean coefficient of thermal expansion for unaged specimens decreased by 70% from 0% to 60% wood filler content. A linear trend found by least squares was used to describe the change in the coefficient of thermal expansion shown in Figure 5.38 (Devore, 1995). The data does not deviate much from this trend and therefore, appears to be an accurate measure of the thermal expansion for all of the tested groups.

Table 5.15 - Summary of Thermal Expansion Test Results

Percent Wood Flour	Unaged Specimens			Aged Specimens			Percent Change due to Aging
	n ^b	Mean Coef. of Thermal Exp., 1x10 ⁻⁵ /°F (1x10 ⁻⁵ /°C)	COV ^a	n ^b	Mean Coef. of Thermal Exp., 1x10 ⁻⁵ /°F (1x10 ⁻⁵ /°C)	COV ^a	
0	10	8.9 (16.0)	0.03	10	8.6 (15.4)	0.04	NA
20	10	7.2 (12.9)	0.04	10	7.2 (12.9)	0.05	3.5
30	11	5.8 (10.5)	0.10	10	5.6 (10.0)	0.12	2.1
40	10	4.4 (8.0)	0.11	10	4.5 (8.1)	0.12	-0.2
50	10	3.1 (5.5)	0.16	10	3.4 (6.1)	0.13	4.0
60	10	2.6 (4.7)	0.07	10	2.7 (4.8)	0.08	-5.9

^a Coefficient of Variation

^b Number of specimens used to calculate results

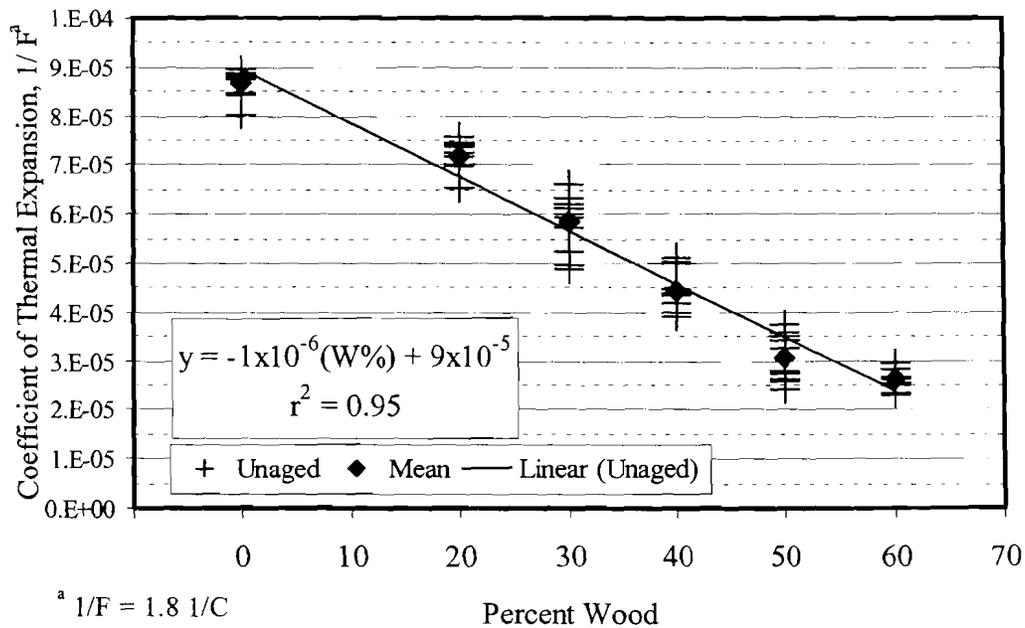


Figure 5.38 - Linear Fit for Unaged Coefficient of Thermal Expansion Data

The statistical analysis of the unaged and aged data is shown in Table 5.16. The P-values are sufficiently high enough to show there is no significant difference between the mean thermal expansion values. Therefore, it was concluded that accelerated aging exposure did not significantly effect the mean values of the two data sets. The 0.997 value for all filler percentages strongly supports this claim when comparing the entire data sets for aged and unaged specimens.

Table 5.16 – T-test P-values of Equal Means for Aged and Unaged Coefficient of Thermal Expansion Data

Wood Flour, %	P-value for Coefficient of Thermal Expansion
0	0.398
20	0.979
30	0.352
40	0.805
50	0.168
60	0.421
All Filler Percentages	0.997

5.7 Fastener Tests

5.7.1 Screw Withdrawal

Tests were performed to determine the fastener properties of wood filled plastic panels. Screw withdrawal was considered to be of primary importance for wood-plastic panels and therefore, a t-test of the aged and unaged data was performed.

Figure 5.39 displays the four types of failures found in the screw withdrawal test. This can be attributed to the bonding of the panel samples together to achieve the required thickness.

Specimen A was the most common screw withdrawal failure for all wood flour percentages. The material failed locally around the screw threads along the entire length of

the screw. Specimens B and D failed in a similar manner. The top sample separated along its mid-plane allowing the material to raise with the screw. Specimen B shows a relatively



Figure 5.39 – Screw Withdrawal Failures. A) local material failure, B) material bonding failure, C) delamination and flexural failure, D) large diameter material bonding failure.

smaller raised area, and specimen D has a large diameter but with less vertical separation from the base sample. Specimen C delaminated due to a poor glue bond between the samples. The large crack across the top resulted from localized flexural failure.

The load to pull the screw from the specimen was recorded per inch of screw embedment. Results are shown in Figure 5.40. Table 5.17 summarizes the test results.

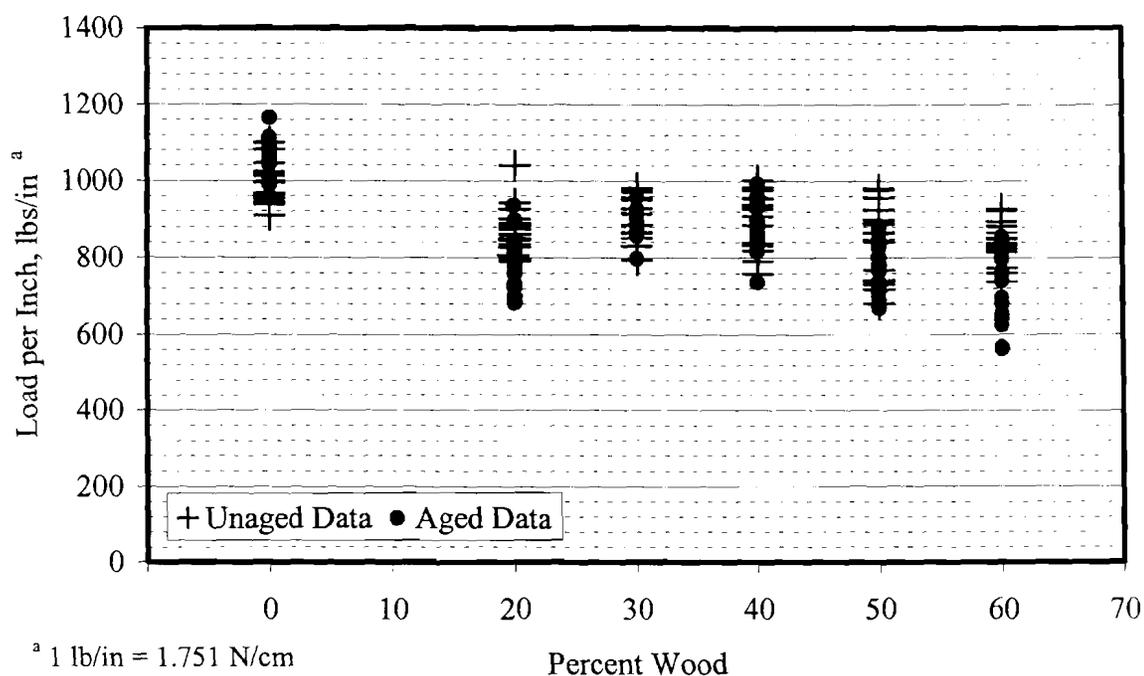


Figure 5.40 - Screw Withdrawal Load Comparison for Aged to Unaged Specimens

Table 5.17 - Summary of Screw Withdrawal Test Results

Percent Wood Flour	Unaged Specimens			Aged Specimens			Percent Change due to Aging
	n ^b	Mean Screw Withdrawal Load, lbs/in (N/cm)	COV ^a	n ^b	Mean Screw Withdrawal Load, lbs/in (N/cm)	COV ^a	
0	20	995 (1740)	0.05	18 ^c	1050 (1850)	0.05	6.2
20	19 ^c	870 (1520)	0.07	17 ^c	785 (1380)	0.09	-9.2
30	16 ^c	905 (1580)	0.07	17 ^c	885 (1550)	0.04	-2.2
40	15 ^c	905 (1580)	0.08	18 ^c	895 (1570)	0.07	-1.1
50	17 ^c	855 (1500)	0.10	16 ^c	780 (1360)	0.08	-9.0
60	20 ^c	855 (1500)	0.07	17 ^c	730 (1280)	0.12	-14.4

^a Coefficient of Variation

^b Number of specimens used to calculate results

^c Material flaw in unreported specimens or lack of test specimens

The wood content did not effect the screw withdrawal capacity of unaged composite panels as found in other tests. A constant fit shown in Figure 5.41 was computed using the average mean unaged values for the withdrawal load per inch of screw penetration. The 0% wood filler content data was excluded from the trend because of the uncharacteristically high withdrawal values. HDPE may have a higher resistance to screw withdrawal than the resins used in the remaining groups. Values for 20% wood filler samples may be low due to material delamination of the glued samples as previously described. The flexure of the remaining sample causes the hole in the material to open wider on the top surface of the panel. This lowers the friction between the screw and the hole thus causing a lower withdrawal load.

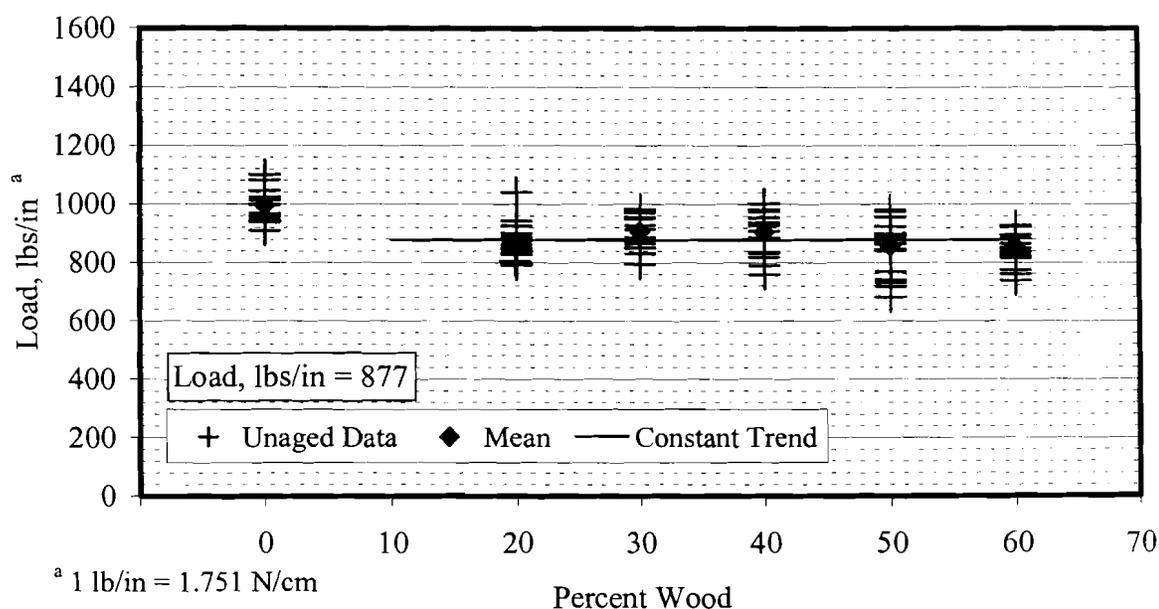


Figure 5.41 - Constant Fit for the Screw Withdrawal Load.
This fit does not include 0 % wood filler content results.

Accelerated aging did not appear to reduce the overall screw withdrawal capacity considering the mean values changed by less than 15%. The statistical analysis revealed

that there is significant difference in the mean values as shown in Table 5.18. The low P-values for the 0% and 20% are related to the delamination of the two specimens resulting from the aging exposure. The aging exposure lowered the bonding strength of the glue causing the panels to separate more quickly during the test. Panels with a mid range of wood filler were not significantly effected by the aging process. These panels did not experience difficulties with maintaining the bond. The P-values for the 50% and 60% show that the mean value was changed due to aging. These specimens did not delaminate and therefore, the loss in screw withdrawal capacity must have resulted from aging exposure.

Table 5.18 – T-test P-values of Equal Means for Aged and Unaged Screw Withdrawal Load

Wood Flour, %	P-value of Screw Withdrawal Loads
0	0.001
20	0.001
30	0.436
40	0.832
50	0.027
60	0.000
All Filler Percentages	0.011

5.7.2 Nail Withdrawal

The nail withdrawal tests were conducted in pursuit of two objectives. The first, similar to the screw withdrawal test, was to find the maximum load to remove the fastener. The second, was to explore the effects of predrilling the specimen. There was no visible difference between the predrilled or not predrilled specimens. Figure 5.42 through Figure 5.45 show the withdrawal load for each case. Tables 5.19 and 5.20 summarize the nail withdrawal test results. The load is recorded as divided by the material thickness. Figure 5.46 displays the effect of the accelerated aging process on the peak loads.

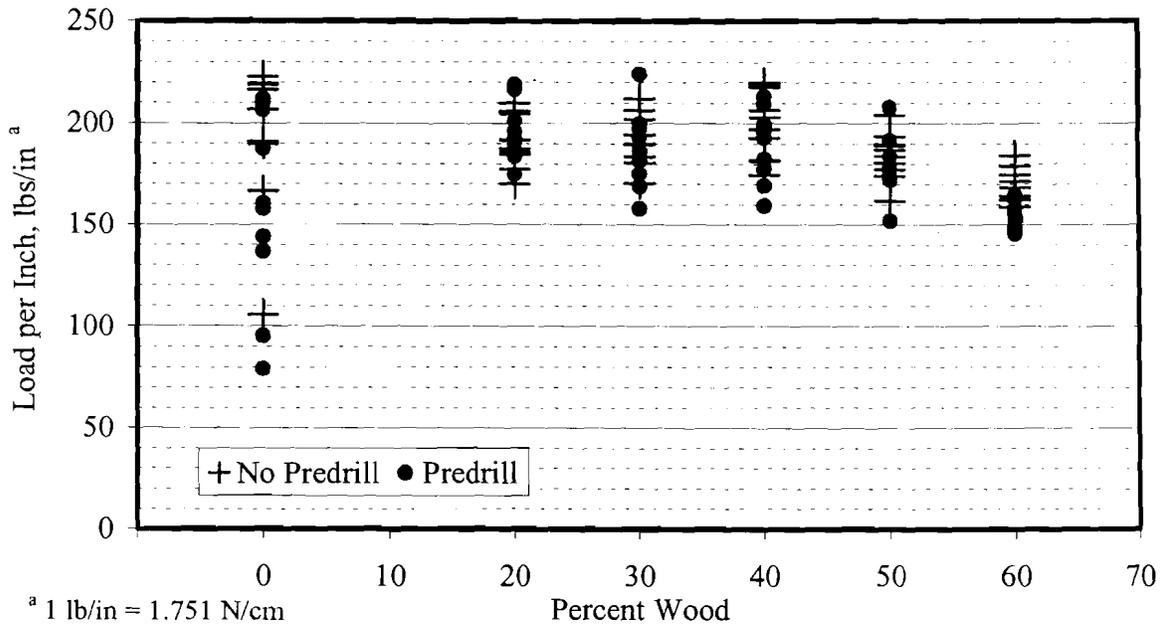


Figure 5.42 - Effect of Predrilling on Nail Withdrawal Load for Unaged Specimens

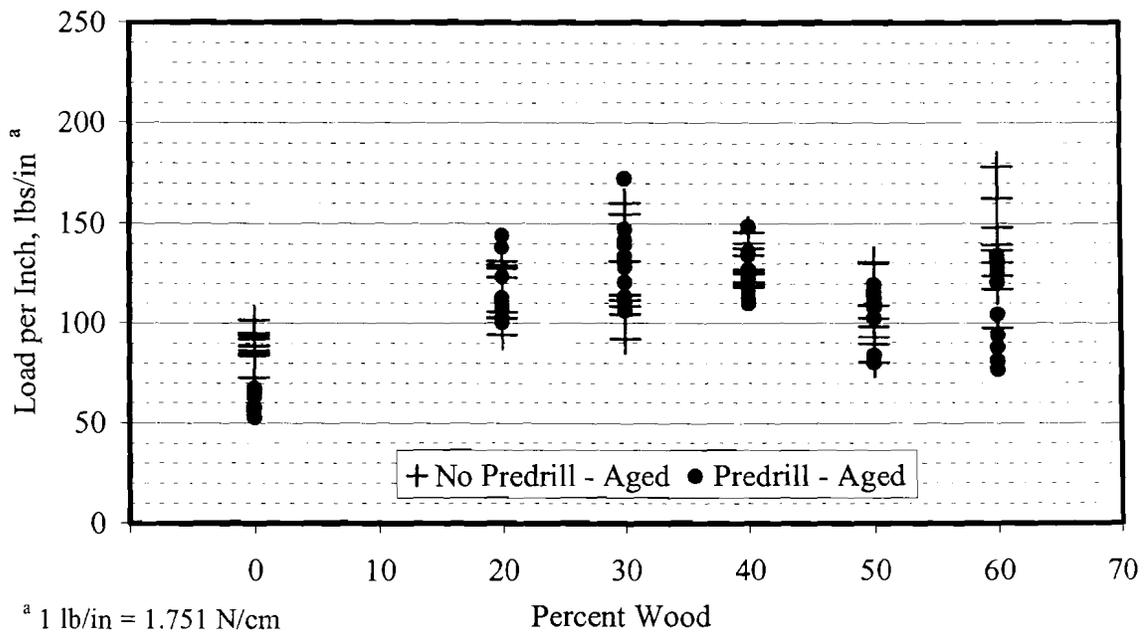


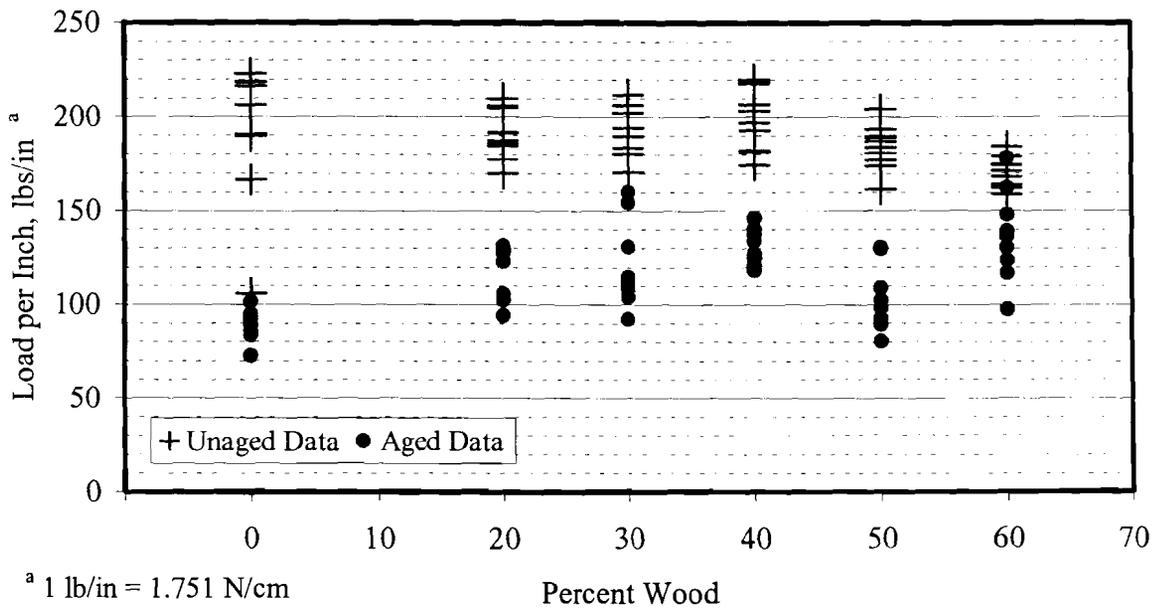
Figure 5.43 - Effect of Predrilling on Nail Withdrawal Load for Aged Specimens

Table 5.19 – Summary of Nail Withdrawal Test Results for Predrilled Specimens

Percent Wood Flour	Unaged Specimens			Aged Specimens		
	n ^b	Mean Predrilled Withdrawal Load, lbs/in, (N/cm)	COV ^a	n ^b	Mean Predrilled Withdrawal Load, lbs/in, (N/cm)	COV ^a
0	10	160 (280)	0.29	10	60 (105)	0.09
20	10	200 (345)	0.08	10	115 (200)	0.13
30	10	190 (330)	0.10	10	130 (230)	0.15
40	10	190 (330)	0.09	10	125 (220)	0.09
50	10	180 (310)	0.08	10	105 (185)	0.14
60	10	155 (270)	0.04	10	110 (190)	0.20

a Coefficient of Variation

b Number of specimens used to calculate results



^a 1 lb/in = 1.751 N/cm

Figure 5.44 - Effect of Aging on Nail Withdrawal Test Comparison of Aged to Unaged Specimens

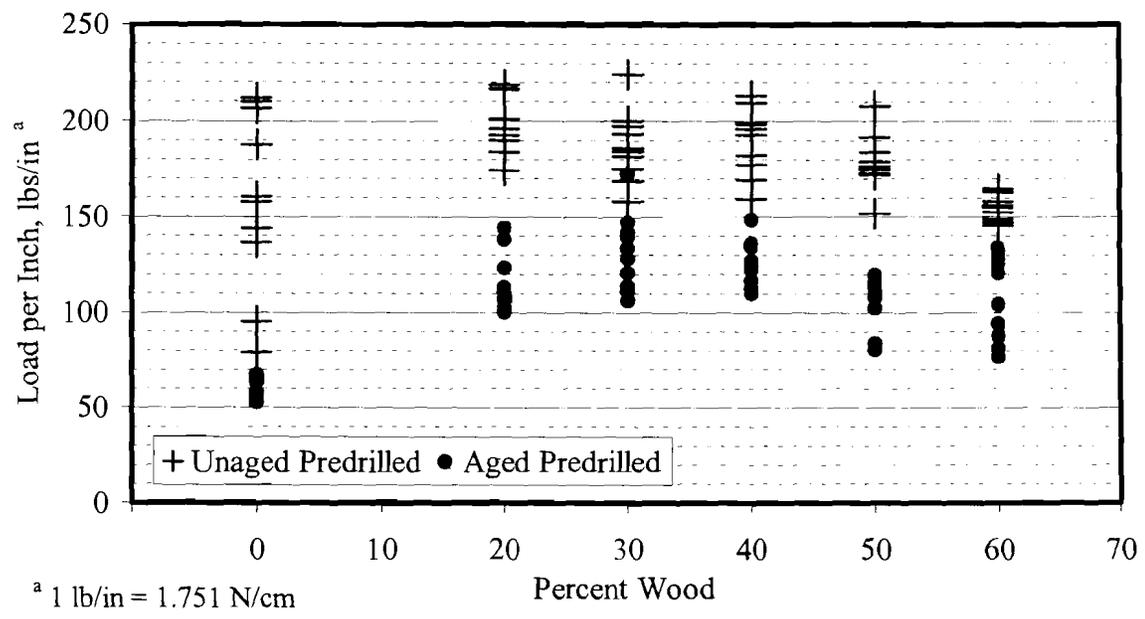


Figure 5.45 - Effect of Aging on Predrilled Nail Withdrawal Comparison of Aged to Unaged Specimens.

Table 5.20 – Summary of Nail Withdrawal Test Results for not Predrilled Specimens

Percent Wood Flour	Unaged Specimens			Aged Specimens		
	n ^b	Mean Not Predrilled Withdrawal Load, lbs/in, (N/cm)	COV ^a	n ^b	Mean Not Predrilled Withdrawal Load, lbs/in, (N/cm)	COV ^a
0	10	190 (335)	0.19	10	90 (155)	0.09
20	10	190 (335)	0.07	8 ^c	115 (200)	0.13
30	9 ^c	190 (335)	0.07	9 ^c	120 (210)	0.19
40	10	200 (350)	0.08	10	130 (225)	0.07
50	10	185 (320)	0.06	10	110 (185)	0.17
60	10	170 (300)	0.05	9 ^c	140 (240)	0.18

a Coefficient of Variation
 b Number of specimens used to calculate results
 c Defect in material and/or nail

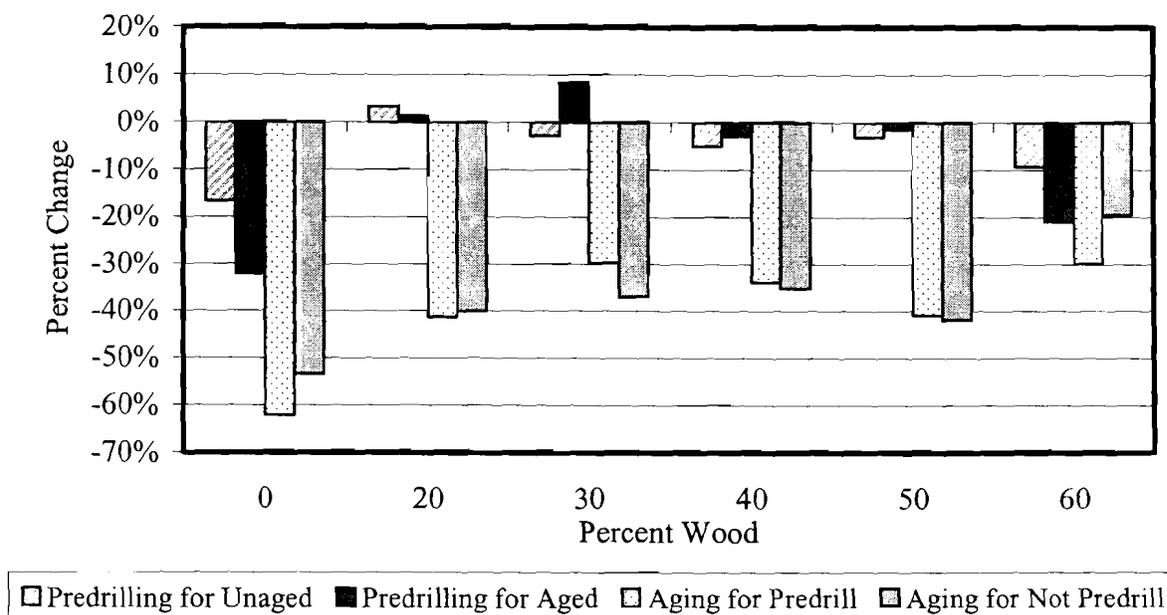


Figure 5.46 - Effect of Aging and Predrilling on Nail Withdrawal Load

The nail withdrawal results were inconsistent between wood percentages and showed high variability in the results. Some general conclusions were formulated from the overall results.

Predrilling did not alter the nail withdrawal capacity of the material except for the 0 percent wood filled panels. The mean change was typically below 5% for the wood filled panels. This change is very small considering the variability found in the test results.

The aging process had a significant impact on the withdrawal loads. Changes in load per inch of nail embedment were up to 62%. Unlike other tests where aging had an adverse effect on the higher wood content specimens, the nail withdrawal loads were reduced for all panel groups. Therefore, explanations other than material degradation from the accelerated aging process should be considered. It has been shown for seasoned wood

that the nail withdrawal capacity of lumber is reduced by time (FPL, 1987). This time based decrease in load was attributed to the stress relaxation of the material. Although not proven for plastic materials, this is a likely explanation for the drop in withdrawal load.

5.7.3 Lateral Nail Resistance

The maximum lateral load to dislodge a fastener $\frac{1}{2}$ -in from the edge of a panel was determined. The material failure was very ductile for low percentages of wood as shown in Figure 5.47. As the wood percentage increased, the material strain was significantly reduced. The nail yielded in most cases from the bending stress induced by the testing fixture before the peak lateral load was reached. Figure 5.48 shows the test data and Table 5.21 summarizes the testing results.



Figure 5.47 – Lateral Nail Resistance Failures of 0% Wood Filler Content. Left: aged specimen, right: unaged specimen. Note how nails are bent upward.

The lateral load required to pull a nail through a panel changed with the percentage of wood filler. A 62% decrease in load was found between 0% wood and 60% wood filler content. A linear fit to the unaged data using least squares describe this change and is shown in Figure 5.49 (Devore, 1995).

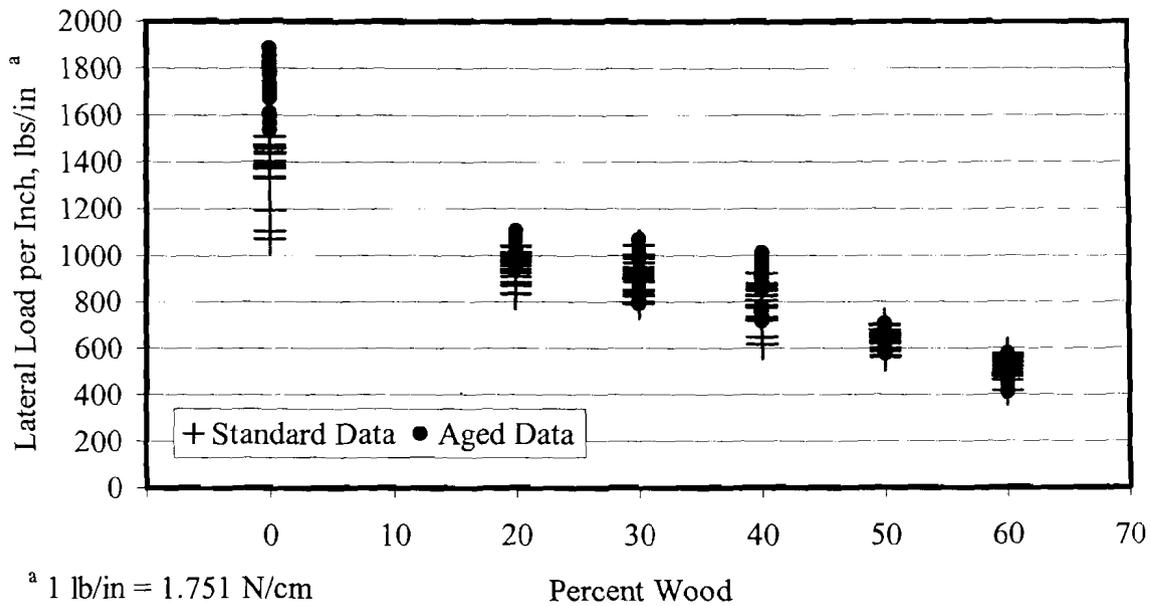


Figure 5.48 - Lateral Nail Resistance Load Comparison of Aged to Unaged Specimens.

Table 5.21 - Summary of Lateral Nail Resistance Test Results

Percent Wood Flour	Unaged Specimens			Aged Specimens			Percent Change due to Aging
	n ^b	Mean Lateral Nail Resistance Load, lbs/in (N/cm)	COV ^a	n ^b	Mean Lateral Nail Resistance Load, lbs/in (N/cm)	COV ^a	
0	19 ^c	1370 (2400)	0.09	19 ^c	1725 (3020)	0.06	25.8
20	19 ^c	960 (1680)	0.07	20	1020 (1780)	0.05	6.3
30	19 ^c	895 (1570)	0.09	19 ^c	960 (1680)	0.09	7.0
40	19 ^c	780 (1370)	0.10	17 ^c	890 (1560)	0.10	14.0
50	19 ^c	640 (1370)	0.06	19 ^c	645 (1560)	0.06	1.1
60	19 ^c	515 (900)	0.08	20	495 (865)	0.11	-4.0

^a Coefficient of Variation

^b Number of specimens used to calculate results

^c Material flaw in unreported specimens or lack of test specimens

The aging process actually increased the lateral load resistance of the composite panels. This was typically found in lower percentages of wood filler as shown in Figure

5.50. It is doubtful that the material became stronger from the aging process. The best explanation for the change in load is the reduction of the nail area. When high loads were reached, the nails began to bend excessively. As the wood content increased the loads became lower and nails did not bend nearly as much. In the higher percentages of wood filler, the load did not change from the aging process. Certainly, if any panel group is to be altered from aging it is the higher percentage groups. This evidence leads to the conclusion that the change in nail properties must have increased the loads rather than changes in the panel material.

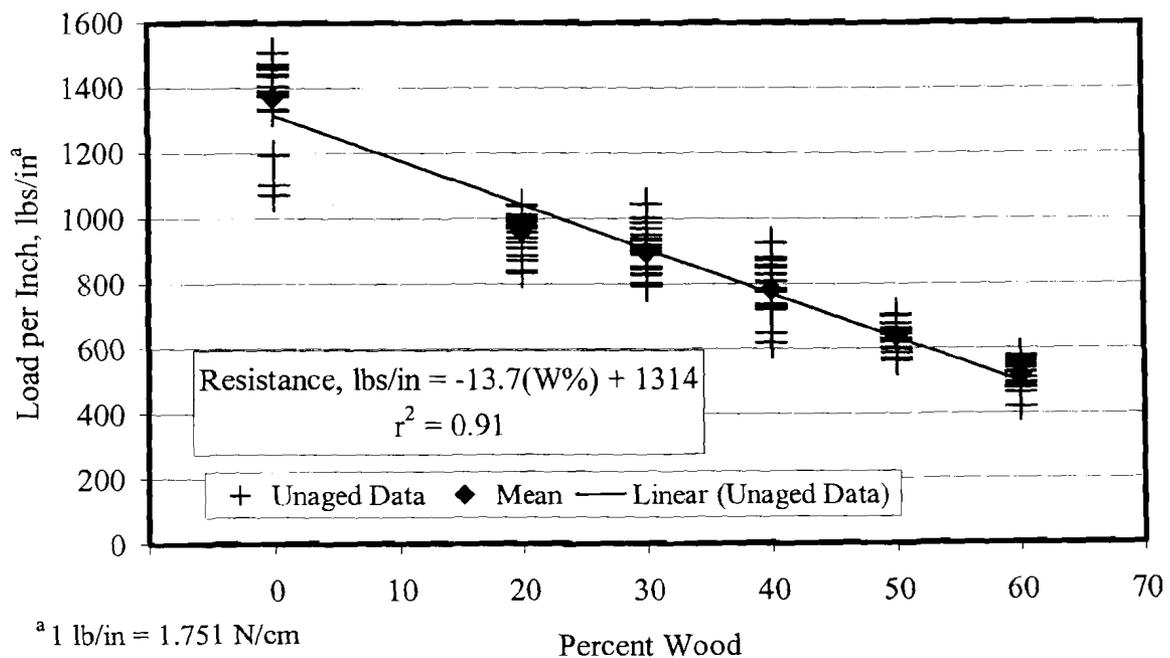


Figure 5.49 - Linear Fit for Unaged Lateral Nail Resistance Load Data

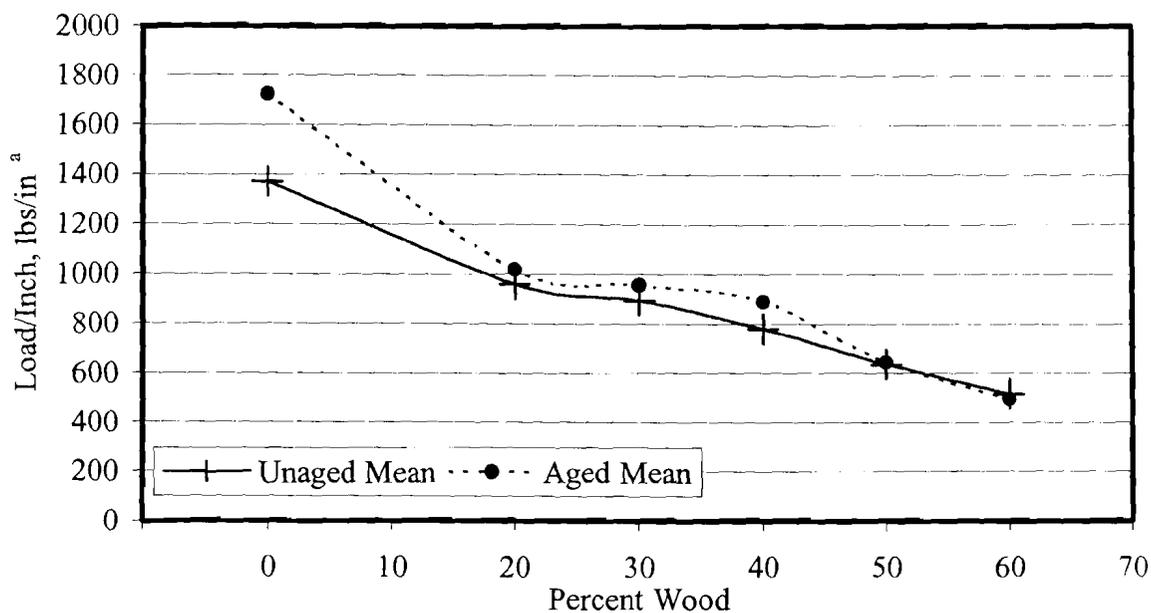


Figure 5.50 - Trends in Mean Lateral Nail Resistance Load for Unaged and Aged Specimens.

5.7.4 Nail Head Pull Through

Similar to the nail withdrawal test, the effect of accelerated aging and predrilling were explored in a nail head pull through test. The nail head displaced the material in the 0% wood specimens. Samples with higher wood content exhibited cracking propagating from the nail. Figures 5.51 through 5.54 show the test data. Tables 5.22 and 5.23 summarize the testing results and Figure 5.55 shows the effect of accelerated aging exposure on the test results. The load values are reported per inch of material thickness.

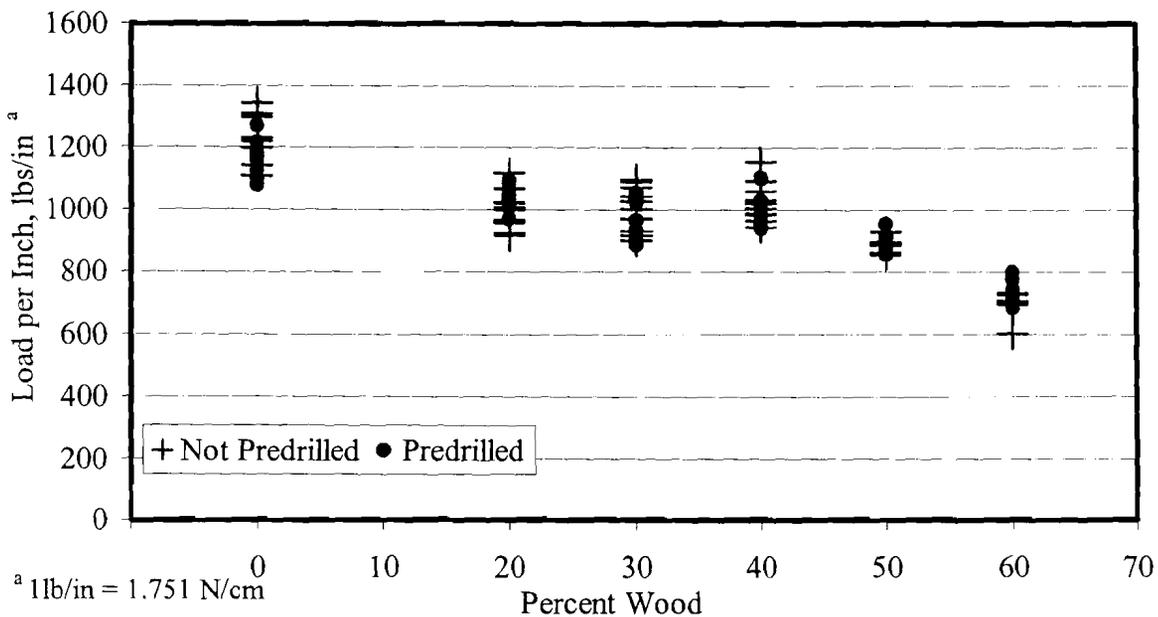


Figure 5.51 - Effect of Predrilling for Nail Head Pull Through Comparison for Unaged Specimens

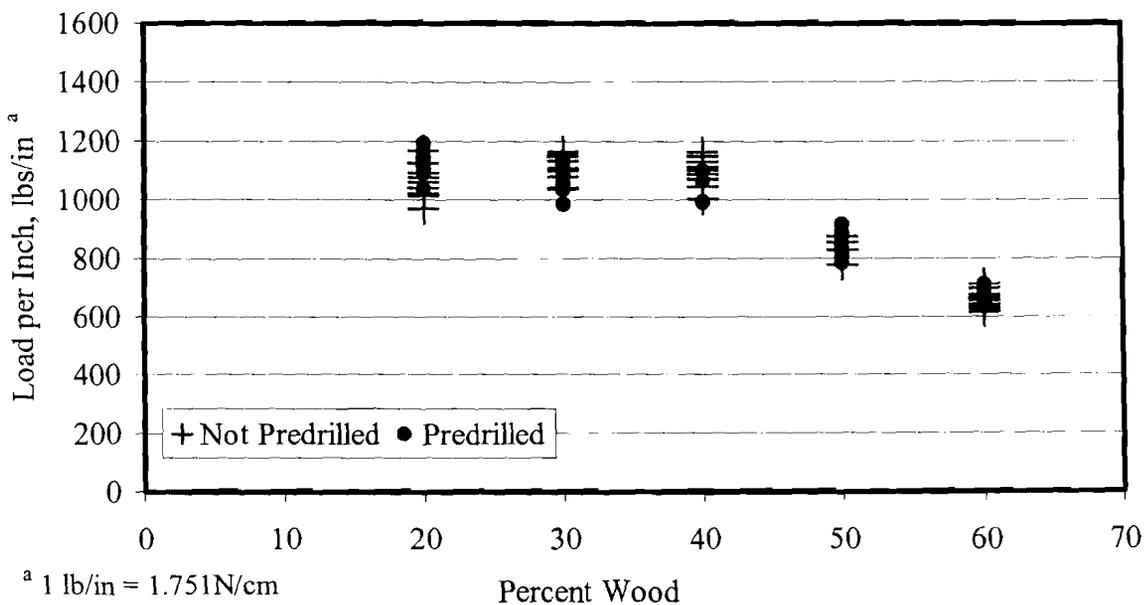


Figure 5.52 - Effect of Predrill on Nail Head Pull Through Load Comparison for Aged Specimens

Table 5.22 – Summary of Nail Head Pull Through for Predrilled Specimens

Percent Wood Flour	Unaged Specimens			Aged Specimens		
	n ^b	Mean Predrilled Pull Through Load, lbs/in, (N/cm)	COV ^a	n ^b	Mean Predrilled Pull Through Load, lbs/in, (N/cm)	COV ^a
0	9 ^c	1240 (2180)	0.07	20 ^d	1295 (2270)	0.07
20	10	1000 (1750)	0.06	9 ^c	1065 (1860)	0.06
30	10	1005 (1760)	0.07	10	1110 (1940)	0.04
40	10	1020 (1790)	0.06	15 ^d	1100 (1920)	0.04
50	8 ^c	885 (1550)	0.03	5 ^c	885 (1550)	0.04
60	10	700 (1230)	0.06	10	660 (1160)	0.05

a Coefficient of Variation

b Number of specimens used to calculate results

c Material flaw in unreported specimens

d Misrepresentation of variable

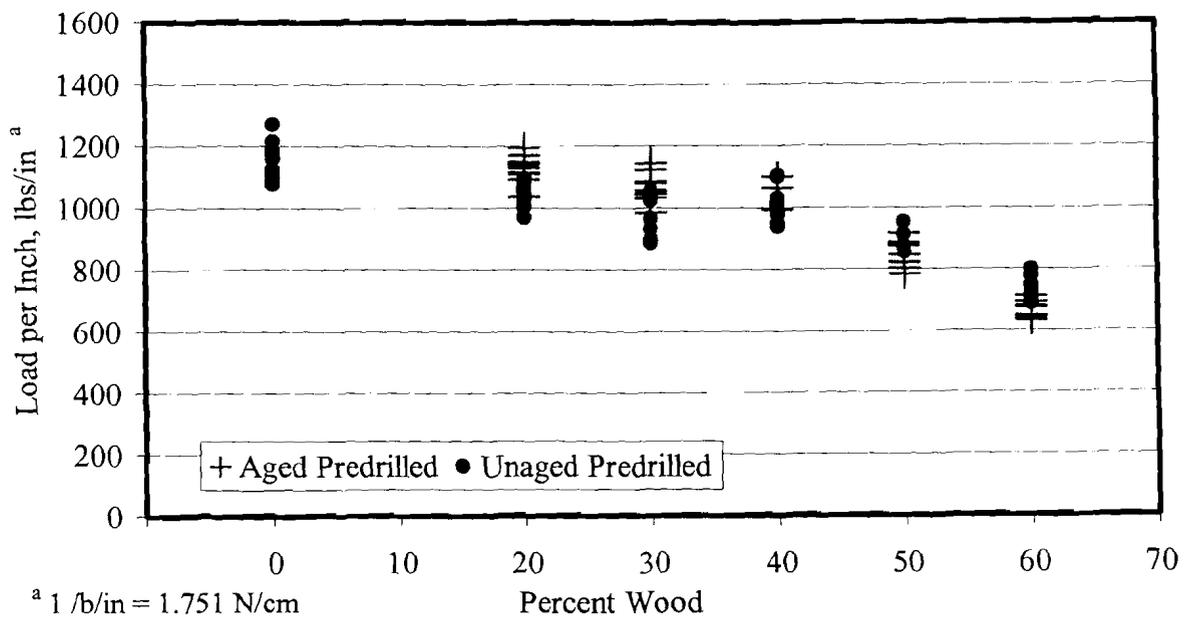


Figure 5.53 - Effect of Aging for Nail Head Pull Through Comparison for Predrilled Specimens

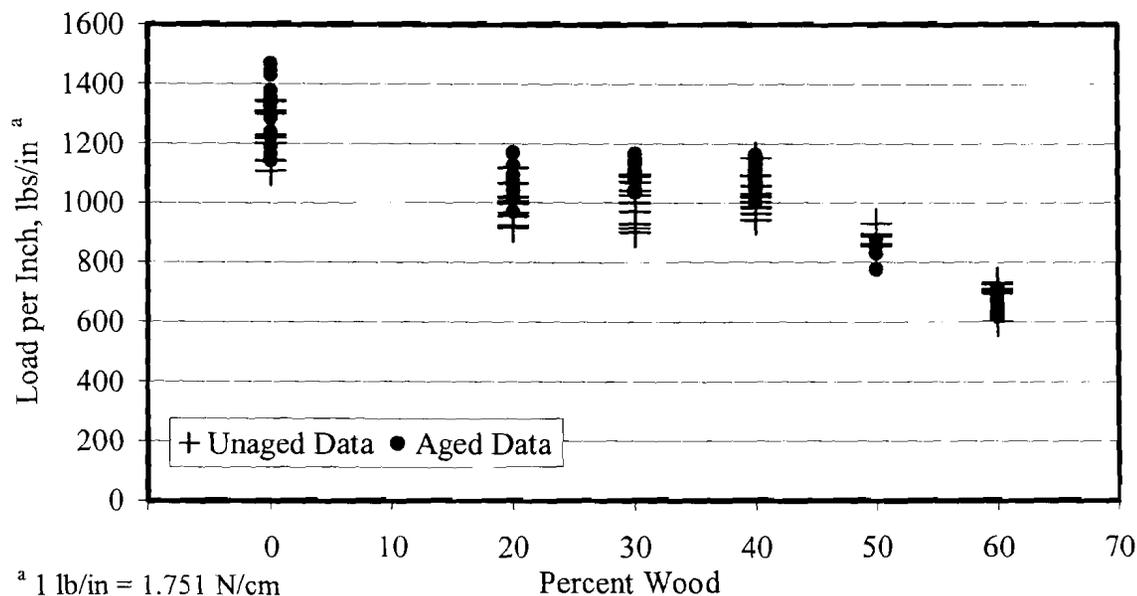


Figure 5.54 - Effect of Aging for Nail Head Pull Through Load for Not Predrilled Specimens

Table 5.23 – Summary of Nail Head Pull Through for Not Predrilled Specimens

Percent Wood Flour	Unaged Specimens			Aged Specimens		
	n ^b	Mean Not Predrilled Pull Through Load, lbs/in, (N/cm)	COV ^a	n ^b	Mean Not Predrilled Pull Through Load, lbs/in, (N/cm)	COV ^a
0	9 ^c	1150 (2020)	0.06	0 ^d	NA	NA
20	10	1040 (1820)	0.04	10	1130 (1975)	0.04
30	9 ^c	970 (1700)	0.07	9 ^c	1070 (1870)	0.05
40	10	1010 (1770)	0.05	4 ^d	1040 (1820)	0.05
50	7 ^c	900 (1570)	0.04	10	850 (1490)	0.05
60	10	730 (1290)	0.04	10	665 (1160)	0.04

a Coefficient of Variation

b Number of specimens used to calculate results

c Material flaw in unreported specimens

d Misrepresentation of variable

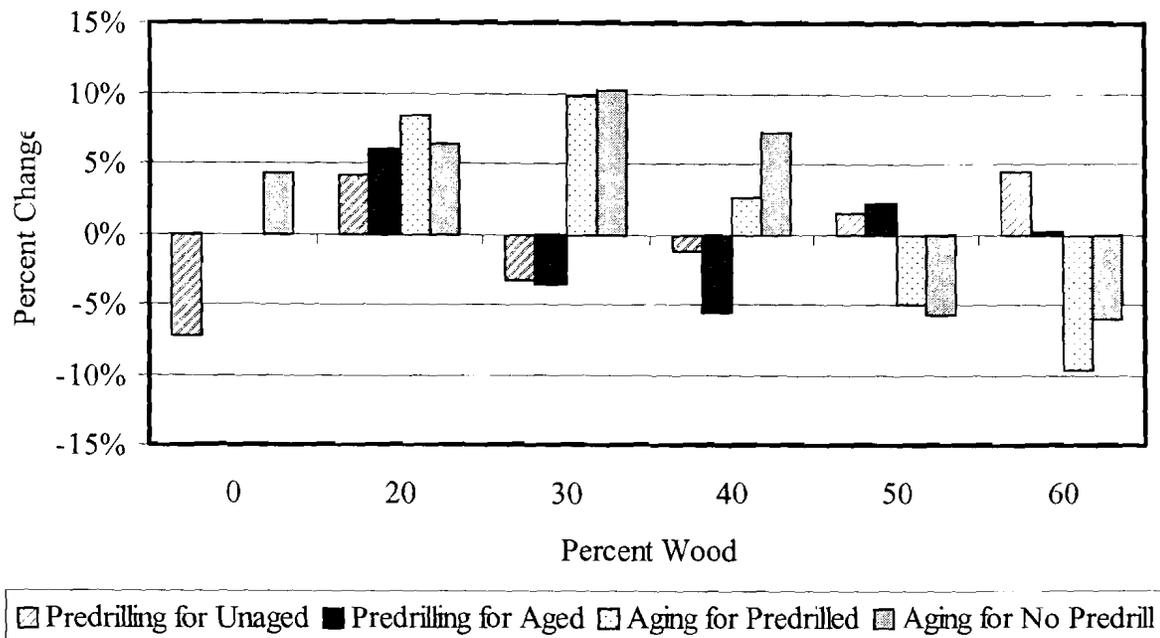


Figure 5.55 - Effect of Aging and Pre-drilling on Nail Head Pull Through Tests

Predrilling the panel before embedding the nail did not significantly alter the peak load. In all cases, no change was greater than 7% resulting from predrilling. This supports a logical assumption that the maximum nail head pull through load is dependent upon the resistance of the material not allowing the nail head to penetrate. Also, there was no change in peak load due to predrilling in the nail withdrawal case.

A linear fit was calculated using least squares to describe the unaged data including both predrilled and not predrilled specimens (Devore, 1995). Figure 5.56 shows the fit to the data. The lower wood percentage groups showed a slight increase in pull through load (~8%) while higher wood content specimens slightly decreased in pull through load (5%) after aging. These changes were independent of the predrilling variable. It is uncertain on whether the aging did have an effect or if the number of samples was too small.

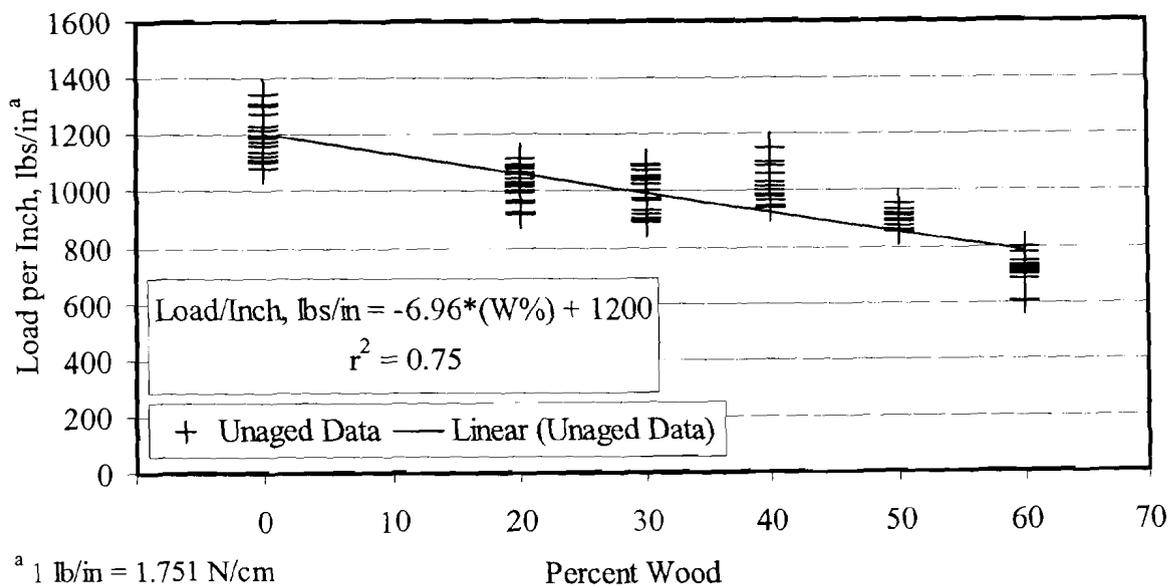


Figure 5.56 - Linear Fit for Unaged Nail Head Pull Through Resistance

Chapter 6 - Comparison to Conventional Wood-Based Panel Products

The results presented in Chapter 5 will be compared to values for common wood-based panel products. This will indicate how the performance of wood-plastic composite panels compares to common wood-based panel products.

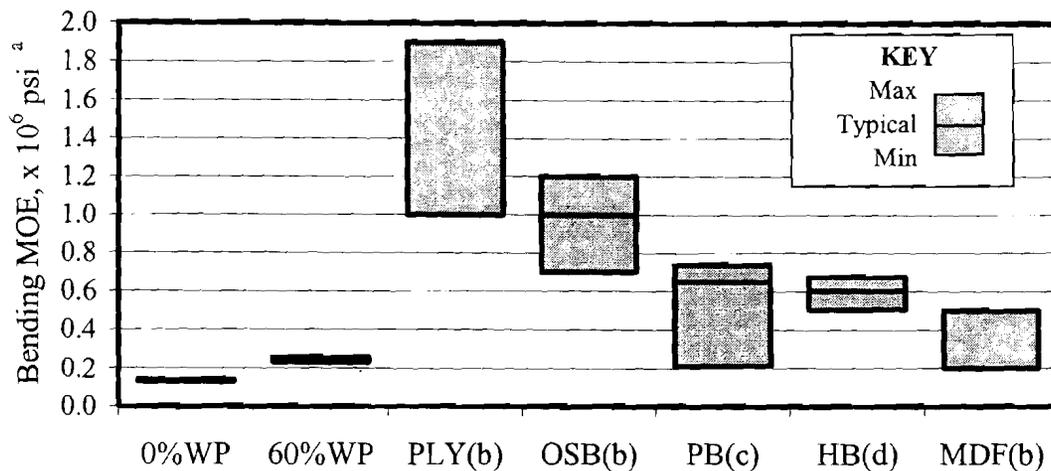
Five conventional wood-based products are offered for comparison in this section chosen due to wide use and availability in the industry. They are plywood (PLY), orientated strand board (OSB), particleboard (PB), standard hardboard (HB), and medium density fiberboard (MDF). The wood-plastic composite panels are represented as 0%WP and 60%WP corresponding to 0% and 60% wood filler content panels, respectively. For some properties, 20% wood filler content panels (20%WP) are substituted when results for the 0% panels were not available from this study.

Panel products are often available in a range of specifications that alter material performance (e.g., particleboard is manufactured with different densities that may affect the bending MOE). For that reason, each material is shown as having a range of values denoted as minimum (Min) and maximum (Max). Typical values designate a number that is commonly found for that material. In some cases, only these values were available and are represented as single bars. All of the conventional wood based panel values were obtained from past studies that are referenced in each figure.

The range values for wood-plastics composites were obtained from the results of this study. A larger range would be expected if additional manufactures produced panels to be tested. Typical values are equivalent to the mean results from the tested wood-plastic panels.

As shown in Figure 6.1, the addition of wood filler nearly doubles the bending MOE

of plastic alone, values are still significantly lower than found in conventional wood products. Panels with a high wood filler content are comparable with the lower range values of PB and MDF.



^a 1 psi = 0.006895 MPa

^b From Wood Handbook, 1998

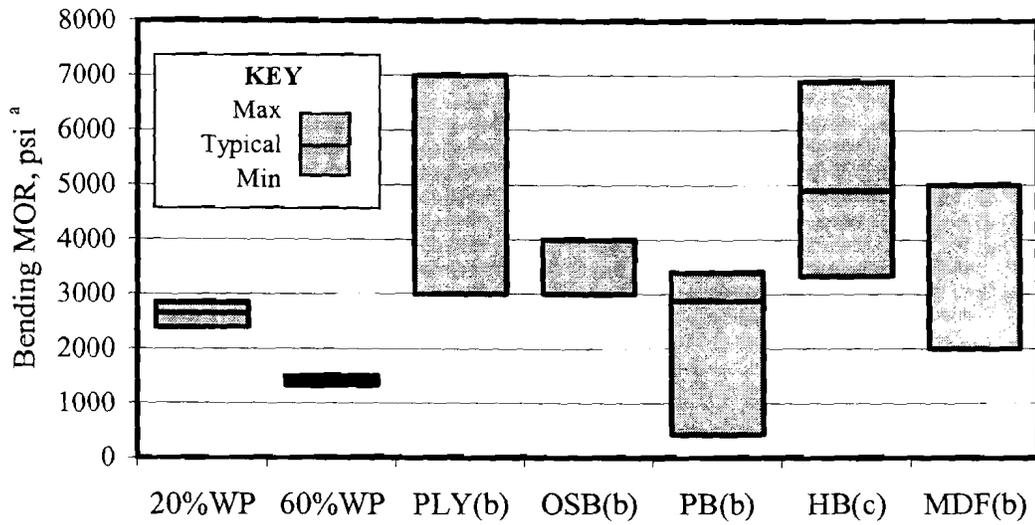
^c From Lehmann, 1974 and Geimer, 1973

^d From McNatt, April 1993

Figure 6.1 – Comparison of Bending Modulus of Elasticity Values

Bending MOR values are comparable to those found in the lower range of the conventional panels as shown in Figure 6.2. The 20% wood content composite panel is in the range of strength of OSB, PB, and MDF.

Figure 6.1 shows that the bending MOE for wood-plastic composite panels was low when compared to conventional wood-based panels. After the aging exposure, conventional materials undergo substantial reductions in bending MOE. After the ASTM D1037 exposure, wood-plastic composites are nearly equivalent to typical values for PB and HB as shown in Figure 6.3.

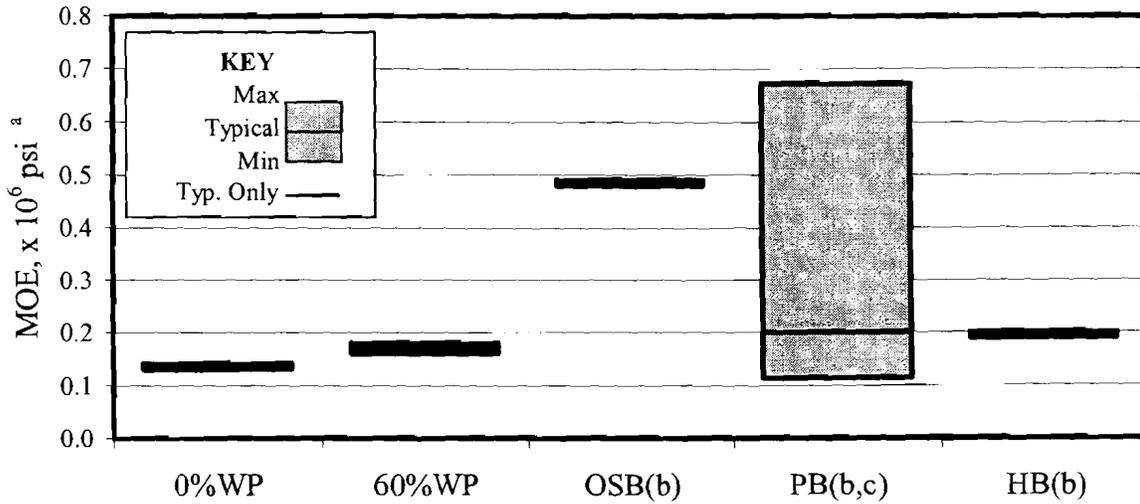


^a 1 psi = 0.006895 MPa

^b From Wood Handbook, 1998

^c From McNatt, 1989, McNatt, April 1993, Superfesky, 1974

Figure 6.2 – Comparison of Bending Modulus of Rupture Values



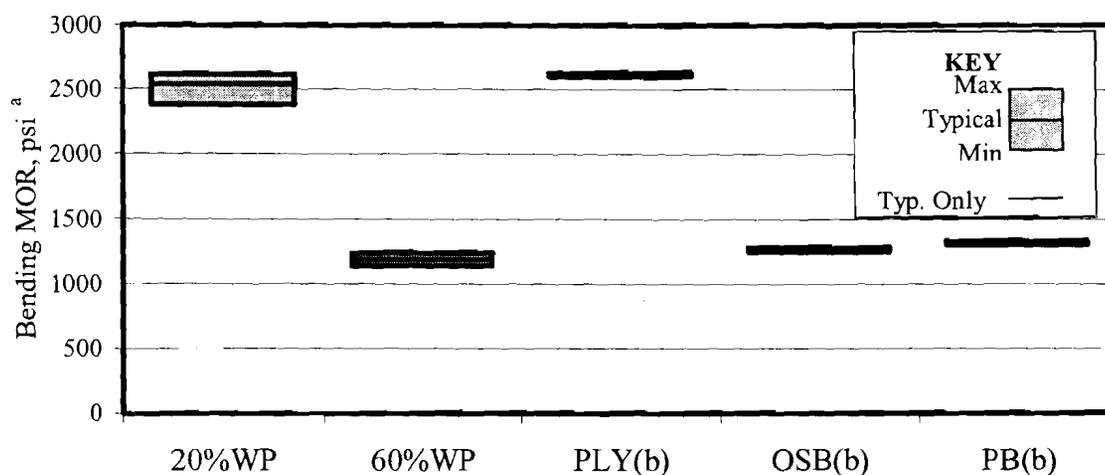
^a 1 psi = 0.006895 MPa

^b From McNatt, 1989

^c From McNatt, 1989 and Lehmann, 1974

Figure 6.3 – Comparison of Aged Bending Modulus of Elasticity Values

Accelerated aging bending MOR values are comparable to conventional products as shown in Figure 6.4. The typical values of plywood, OSB, and PB have a similar range compared to the typical values of wood-plastic panels. While the wood-plastic composite MOR values initially appear inferior to the conventional panels, the values are in the same range after the accelerated aging exposure is considered.



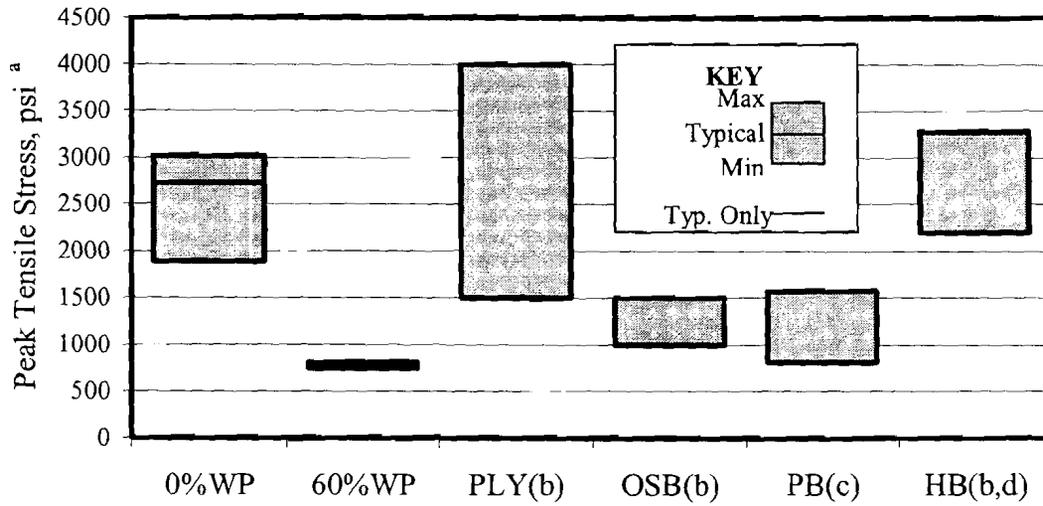
^a 1 psi = 0.006895 MPa

^b From McNatt, 1989

Figure 6.4 – Comparison of Aged Bending Modulus of Rupture Values

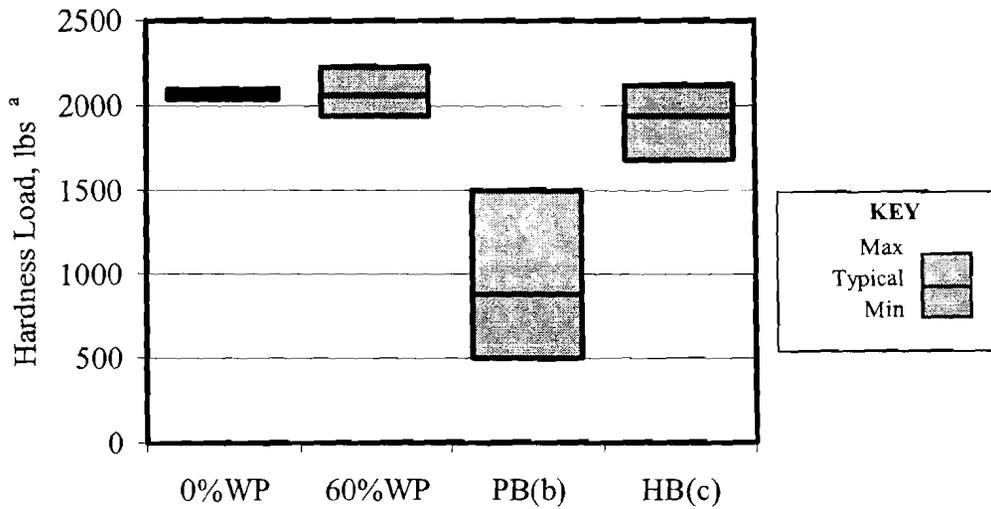
The tensile strength of 0%WP is moderate when compared with other stress values as shown in Figure 6.5. This value drops as wood filler content increases bringing wood-plastic composites to the lower range of the panel products.

Hardness properties, shown in Figure 6.6, are higher for wood-plastic panels than other composite products. PB is often used in flooring applications. Certainly wood-plastic has an acceptable hardness capacity for this use. Referring to Figure 6.7, the hardness modulus showed similar results to the hardness load.



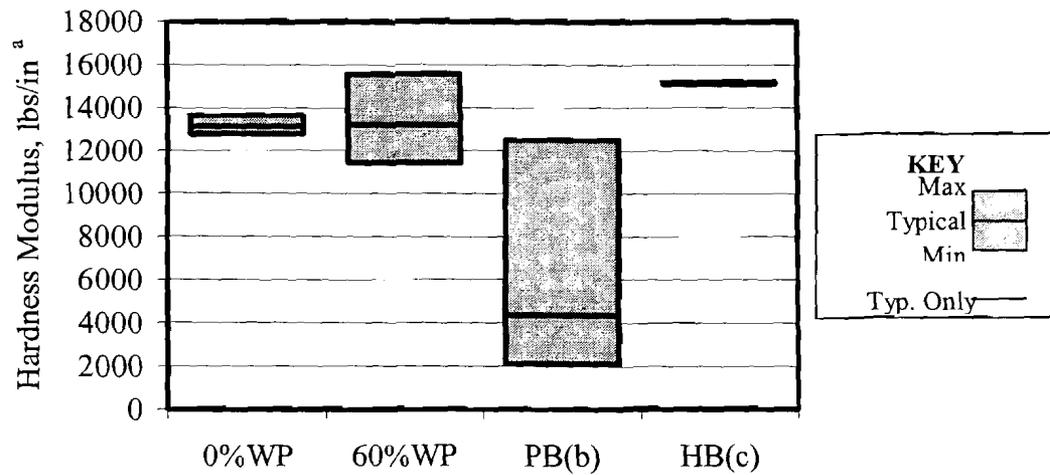
^a 1 psi = 0.006895 MPa
^b From Wood Handbook, 1998
^c From McNatt, 1973
^d From McNatt, April 1993

Figure 6.5 – Comparison of Tensile Strength Values



^a 1 lb = 4.448 Newtons
^b From Wood Handbook, 1998
^c From Lewis, 1968

Figure 6.6 – Comparison of Hardness Load Values



^a 1 lb/in = 1.751 N/cm

^b From Wood Handbook, 1998

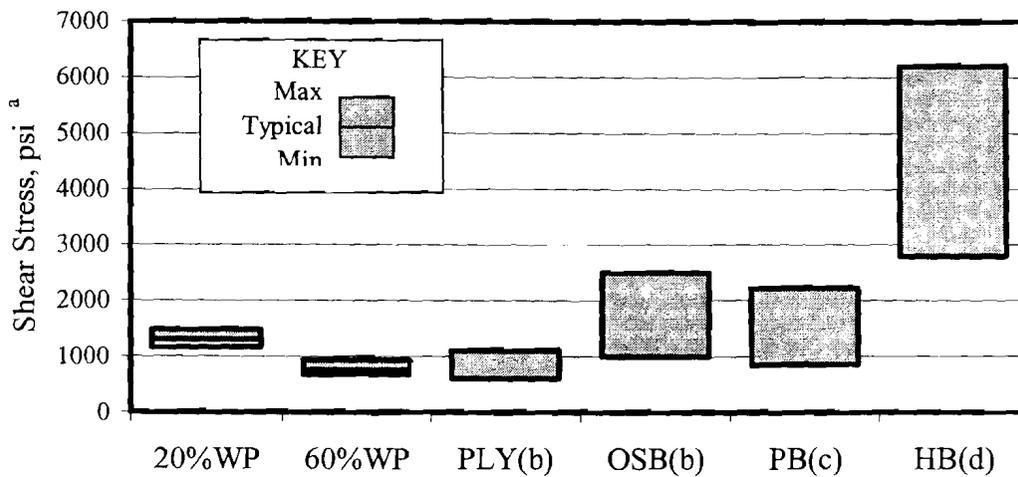
^c From Lewis, 1968

Figure 6.7 – Comparison of Hardness Modulus Values

In shear, wood-plastic composite panels perform similarly in shear strength to most conventional wood-based products as shown in Figure 6.8. The decrease in shear strength should not limit the material considering the fact that other materials like plywood have a similar stress range. Only HB has a significantly higher resistance to shear forces.

Wood-plastic composites have a high resistance to moisture absorption. The values presented in Figure 6.9 show the change in the 60% wood filler content panels is negligible when compared to other panel materials.

For the percent weight change, wood-plastic panels exhibit extremely small changes (less than 1%) relative to other common panel materials that swell up to 40% of their original thickness as shown in Figure 6.10. Only MDF has the stability characteristics wood-plastic composites possess.



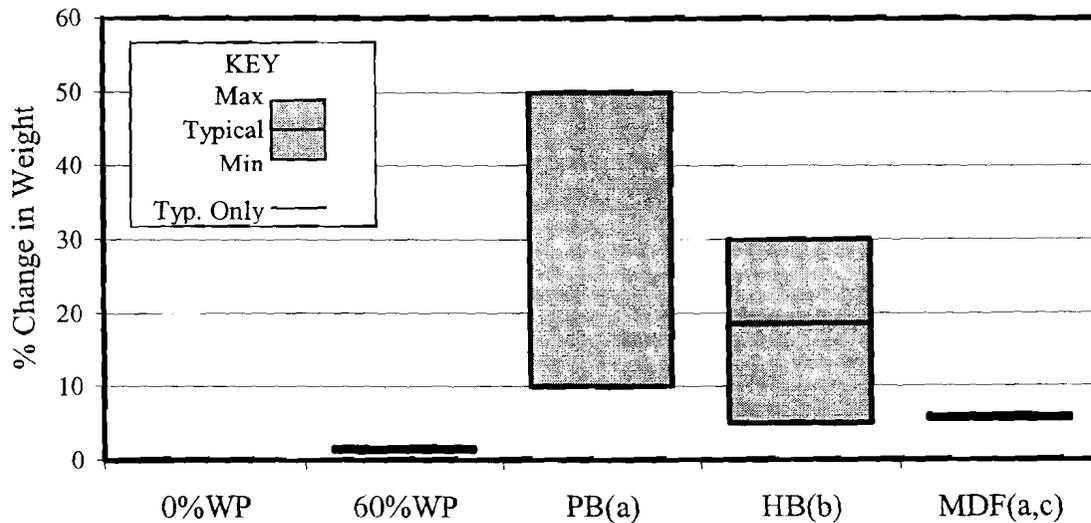
^a 1 psi = 0.006895 MPa

^b From Wood Handbook, 1998

^c From McNatt, 1973

^d From Lewis, 1967

Figure 6.8 – Comparison of Edgewise Shear Strength Values

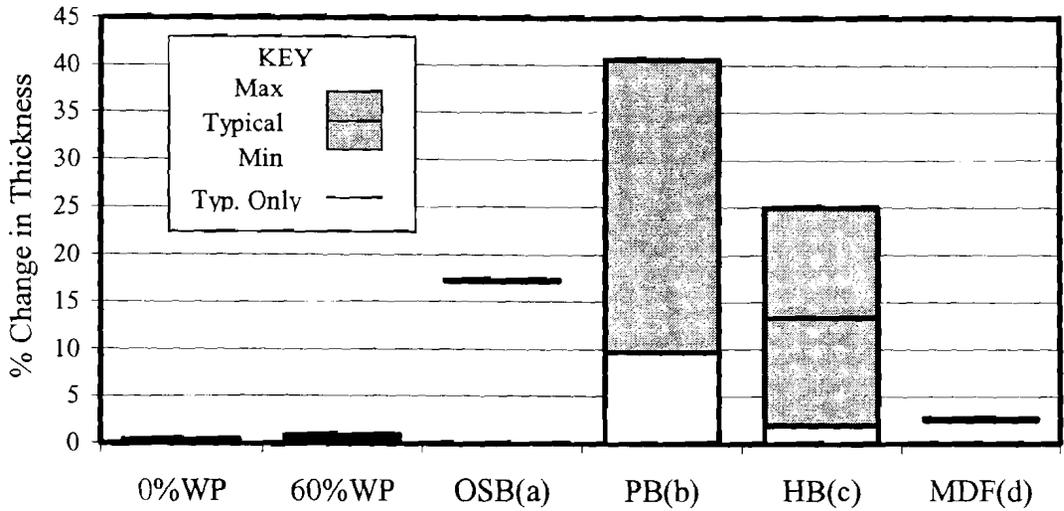


^a From Lewis, 1967

^b From Lewis, 1967

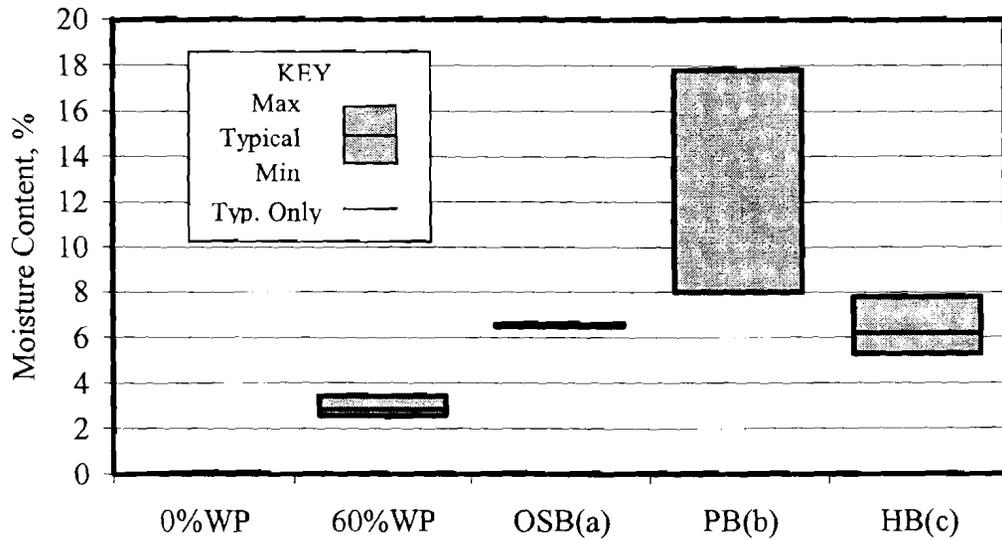
^c From McNatt, July/August 1993

Figure 6.9 – Comparison of Percent Change in Weight after 24-Hour Moisture Absorption Test



^a From McNatt, 1992
^b From Lehmann, 1974
^c From Lewis, 1967 and McNatt, 1993
^d From Lewis, 1967

Figure 6.10 – Comparison of Thickness Swell After 24-Hour Moisture Absorption Test

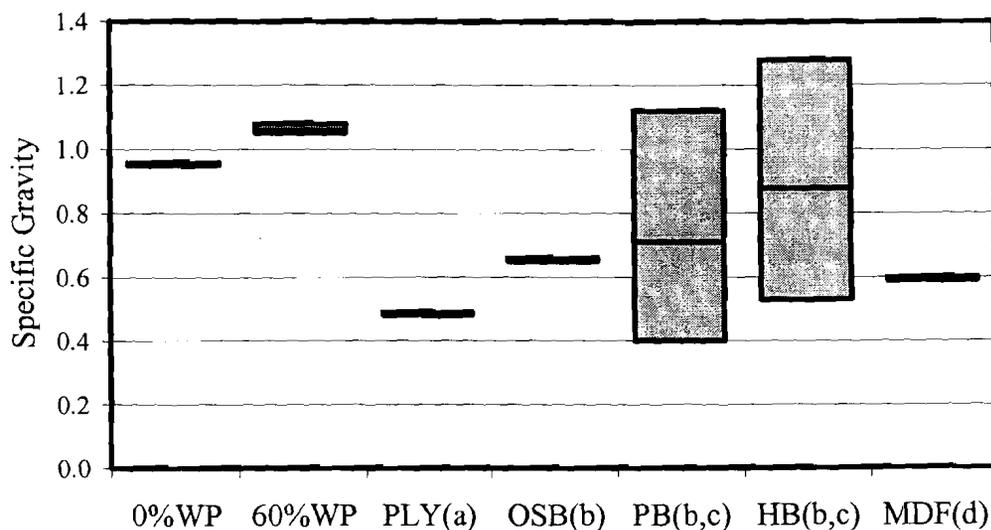


^a From McNatt, 1989
^b From McNatt, 1973
^c From McNatt, April 1993 and Superfesky, 1974

Figure 6.11 – Comparison of Moisture Content Values at 65% Relative Humidity and 72°F

The average specific gravity values for wood-plastic composite panels are higher than all other wood-based materials as shown in Figure 6.12. This may be a disadvantage trying to integrate these products into construction markets, though wood filled plastics are considerably lighter than mineral or glass filled plastics (English, 1995).

A problem often associated with plastics is their high coefficient of thermal expansion. This property is usually considered to be negligible in conventional wood-based panel design. The 60%WP panels approach the typical values for plywood and OSB as shown in Figure 6.13. Depending on the application, a high wood filler content panel may not exhibit large problems with thermal expansion and may possibly be considered as negligible.



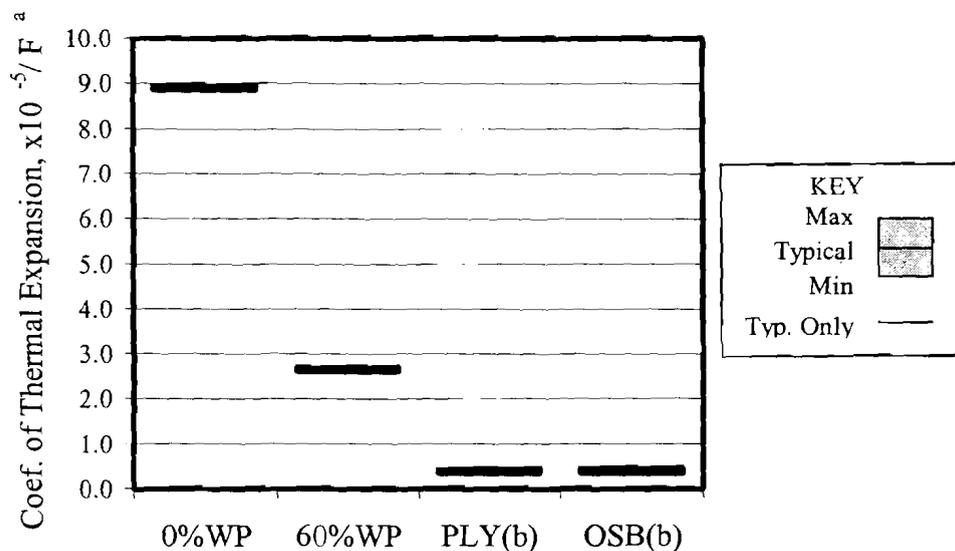
^a Values taken from River, 1994

^b Values taken from McNatt, 1989

^c Values taken from Lewis, 1967

^d Values taken from Lewis, 1965

Figure 6.12 – Comparison for Specific Gravity Values



^a 1/°F = 1.8/°C

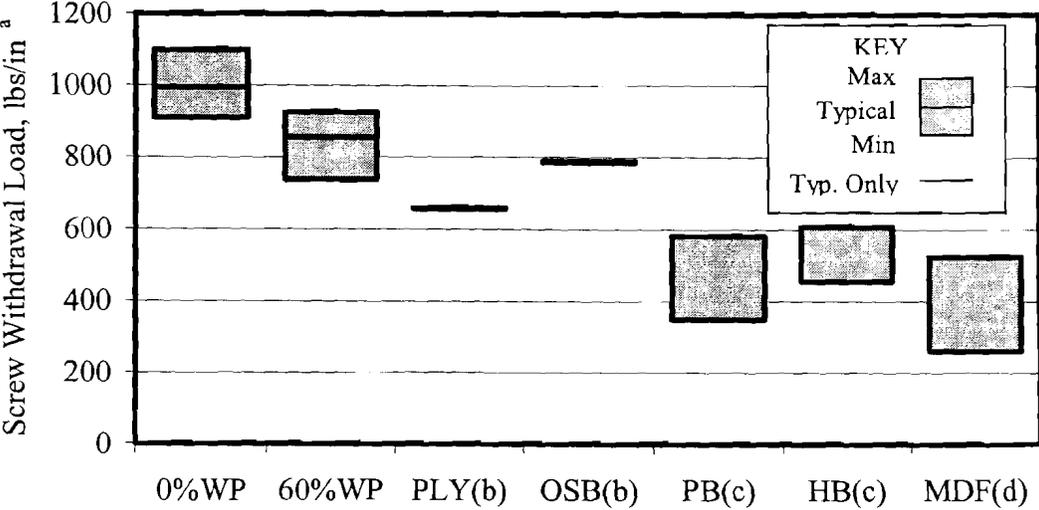
^b From Wood Handbook, 1998

Figure 6.13 – Comparison of Average Coefficient of Thermal Expansion Values

Screw withdrawal loads are higher for wood-plastic composite panels than all other materials considered in this section as shown in Figure 6.14. Only OSB has a resistance to screw withdrawal approaching the wood-plastic panels.

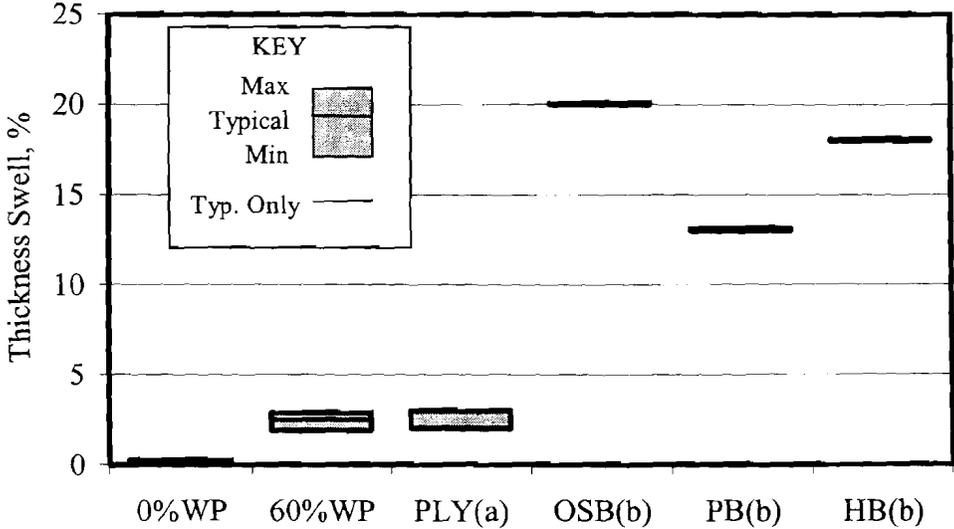
Comparisons for nail performance are not included due to a lack of readily available data with similar testing criteria on composite panels. For lateral nail resistance, PB was found to have a similar resistance load to 0%WP (Lehmann, 1974).

A material's reactivity to aging is often measured by its permanent change in thickness caused by weathering or an accelerated aging exposure. The permanent thickness swell for wood-plastic composite panels due to accelerated aging is extremely low compared to OSB, PB, and HB as shown in Figure 6.15. The dimensional changes due to accelerated aging exposure are included in Appendix C.



^a 1 lb/in = 1.751 N/cm
^b From Liu, 1995
^c From Superfesky, 1974
^d From Wood Handbook, 1998

Figure 6.14 – Comparison of Peak Screw Withdrawal Values



^a From Sellers, 1998
^b From McNatt, July/August 1993

Figure 6.15 – Comparison of Permanent Thickness Swell Values that Resulted from Accelerated Aging Exposure.

As a general assessment of wood-plastic composite panels, Table 6.1 gives an overall comparison of the properties listed in this section considering the general characteristics of wood-based panels collectively. Even though there is a substantial amount of variation in performance between the conventional products, this table depicts some of the overlying differences between wood-plastic panels and conventional wood-based panels. Classifications of “inferior” and “superior” were assigned only if the mean values for wood-plastic composite panels were lower or higher than all mean values found for conventional wood-based panels respectively.

Table 6.1 – General Performance Rating of Wood-Plastic Composite Panels Relative to Conventional Wood-Based Panel Products.

Property	Inferior	Similar	Superior
Bending MOE	X	-	-
Bending MOR	X	-	-
Aged Bending MOE	-	X	-
Aged Bending MOR	-	X	-
Tensile Strength	-	X	-
Hardness Load	-	X	-
Hardness Modulus	-	X	-
Edgewise Shear Strength	-	X	-
Percent Weight Change for 24-Hour Water Soak	-	-	X
Percent Thickness Swell for 24-Hour Water Soak	-	-	X
Specific Gravity	X	-	-
Coefficient of Thermal Expansion	X	-	-
Screw Withdrawal	-	-	X
Thickness Swell due to Aging Exposure	-	-	X

Chapter 7 - Conclusions

Two hypotheses were presented in Chapter 1 regarding the performance of the tested wood-plastic composite panels. The results support the original hypotheses and each corresponding conclusion is shown below.

1. The material stiffness properties were significantly increased with the addition of wood flour to thermoplastic. The bending and tension MOE values increased up to 90% and 61%, respectively, comparing thermoplastic alone to increasing wood flour filler content.

Strength properties decreased linearly with the wood filler content percentage in bending, tension, and shear tests. The resulting decrease in strength for these tests was 48%, 43%, 42%, respectively ranging from 0-60% wood filler. All three tests showed tension failures at peak loads.

The loss in bending strength with the addition of wood flour is inconsequential in service design because the MOE values of the lower wood percentage panels are unable to meet typical deflection requirements. Also, the bending MOR decreased only 48% while the bending MOE increased by 90% comparing the 0% and 60% wood content mean values.

A 40% wood-filler content appears to a practical choice for applications requiring a higher MOE. It would be advisable to avoid using panels with a wood filler content over 40% in applications that may impose cyclical temperature and moisture changes. Mean bending MOE values did not significantly increase above 40% wood filler content based on statistical analysis. Tensile MOE increased up to 61% with the addition of wood flour but these gains were negated by the accelerated

aging exposure. Screw withdrawal mean loads were significantly reduced due to the aging exposure for specimens above 40% wood filler content according to statistical analysis.

Thermoplastic was very resistant to moisture in the 24-hour water soak test. Values for change in weight and volume increased exponentially with the increase in wood filler content. The specific gravity of wood flour was calculated to be 1.15. A 20% - 30% wood filled panel has a specific gravity equal to 1.0. This is substantially lighter than mineral or glass filled plastic panels.

Hardness values are not effected by the filler content. A factor of 6.4 was found relating the hardness load to the hardness modulus.

The addition of wood filler to thermoplastic is beneficial for applications where large temperature variations are expected. By adding wood flour to thermoplastic, the coefficient of thermal expansion is reduced linearly by 70% from 0% to 60% wood filler content.

Predrilling wood-plastic composites does not have an effect on the fastener test properties for the nail withdrawal and nail head pull through tests. The screw and nail withdrawal tests showed a constant trend for removal loads varying the wood filler content. The lateral nail resistance and nail head pull through tests decreased linearly with an increase in wood filler content.

The deterioration caused by the accelerated aging exposure appears to be limited to the exterior surface of the panel. Tests that rely heavily on the exterior surface such as bending and moisture absorption were effected by the aging exposure. A statistical t-test analysis support this conclusion showing very low P-

values for high wood filler content panels for bending MOE, while thermal expansion P-values showed no significant change due to the aging exposure. Conversely, aging did not effect the material properties that are governed by the internal portion of the cross section.

2. Wood-plastic composite panels have acceptable material properties when compared to conventional wood-based panel products currently used in the construction industry. Wood-plastic composites are ideal in high moisture environments with cyclical temperature changes due to their superior resistance to moisture compared with conventional wood-based panel products. This material has not yet been tested for resistance to ultra violet rays.

The modulus of elasticity is the main limiting property for using wood filled panels in structural applications. A second limitation of this material is the high specific gravity when compared with other wood-based panels.

In addition to the hypotheses addressed, the following conclusions resulted from the study.

1. Wood-plastic composite panel products can successfully be manufactured from post-consumer sources.
2. An understanding of the processing methods is critical for producing wood-plastic composites. It is highly recommended to manufacture panels using sheet extrusion or thoroughly heat and mix the material immediately prior to molding.

Chapter 8 - Recommendations for Future Research

The information provided in this study will help the wood-plastic composite market, but there are still questions concerning additional performance specifications. This section suggests future research to further the development of wood-plastic composite panels.

One advantage often associated with using these types of products is their resistance to environmental exposure. These conditions may subject the composite material to direct sun light on a regular basis. Plastic reacts to ultra violet rays causing reductions in the material performance (Osswald, 1996). A study to examine how wood-plastic composite panels react to ultraviolet rays and if enhancers can limit the material degradation is needed.

Time-based deflections from long load durations can be a problem associated with plastic products. The effect of creep on wood-plastic composite panels should be investigated focusing on how the percentage of wood filler effects creep properties.

Currently there are no published standards for the evaluation of wood/plastic composite panels. Since this material behaves quite different than wood, conventional wood standards may not be suitable to evaluate a material of this nature. Research needs to be conducted to evaluate the necessary changes from conventional wood product standards to one that is appropriate for wood/plastic composites.

Possibly the most important aspect for success of these products is understanding the market in which they can be used. Investigations should be made on the appropriate applications for wood-plastic composite materials and how suppliers should address these markets. Studying the material properties alone is not enough to promote the use of composite materials.

Chapter 9 - References

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Appendix A – Test Curves

Appendix A consists of typical load vs. displacement curves for each material property tested, both for unaged and aged specimens. These curves are actual test data and do not include any theoretical fits. The tension curves only include data up to the extensometer removal strain during the testing procedure as described in Chapter 4. Also, moisture absorption curves are not included because only 2 points (2 hours and 24 hours) were measured after the initial conditions. The resulting curve would not be a realistic representation of the actual moisture absorption.

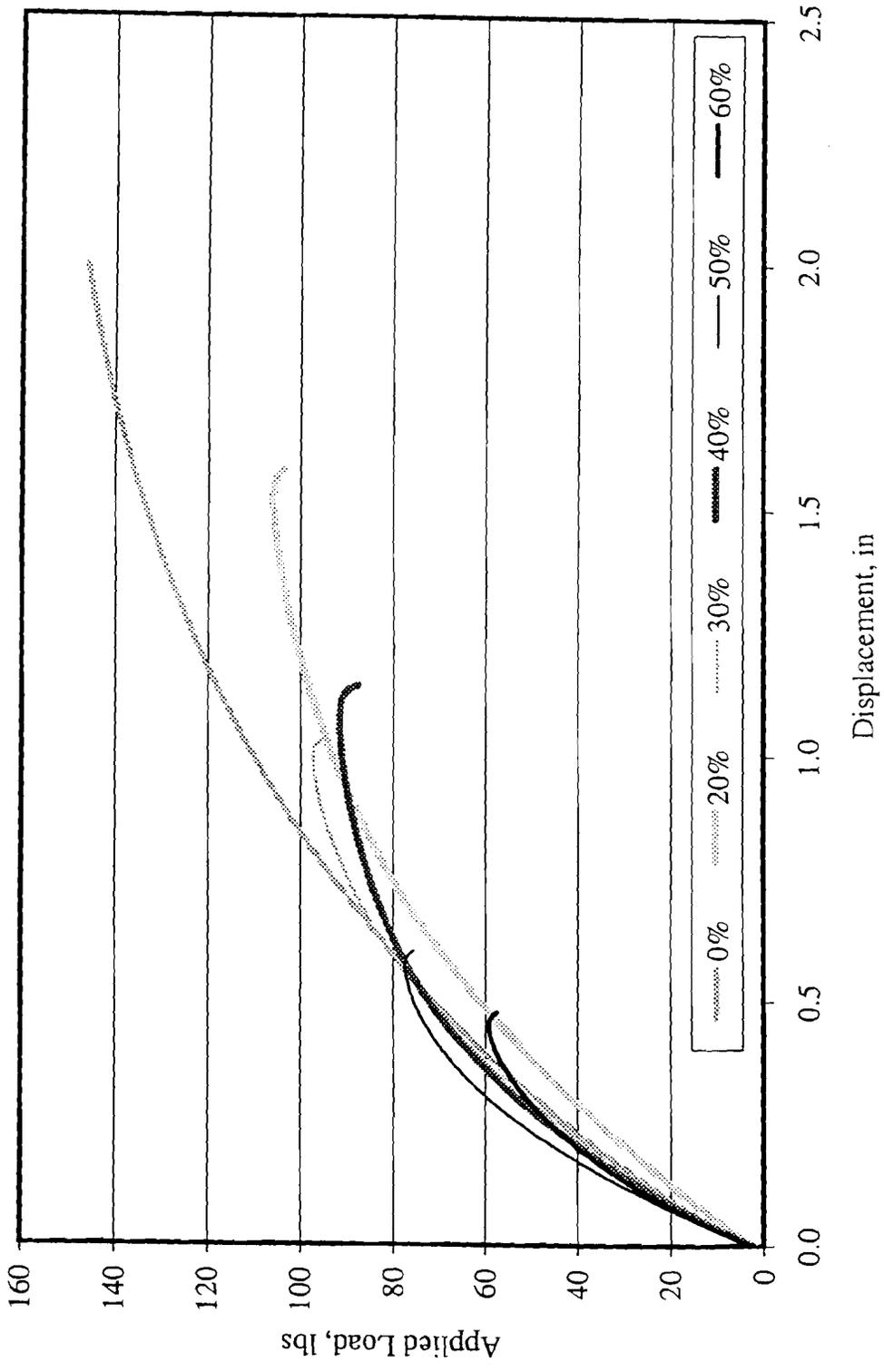


Figure A.1 - Typical Load vs. Displacement Curves for Center Point Bending Tests

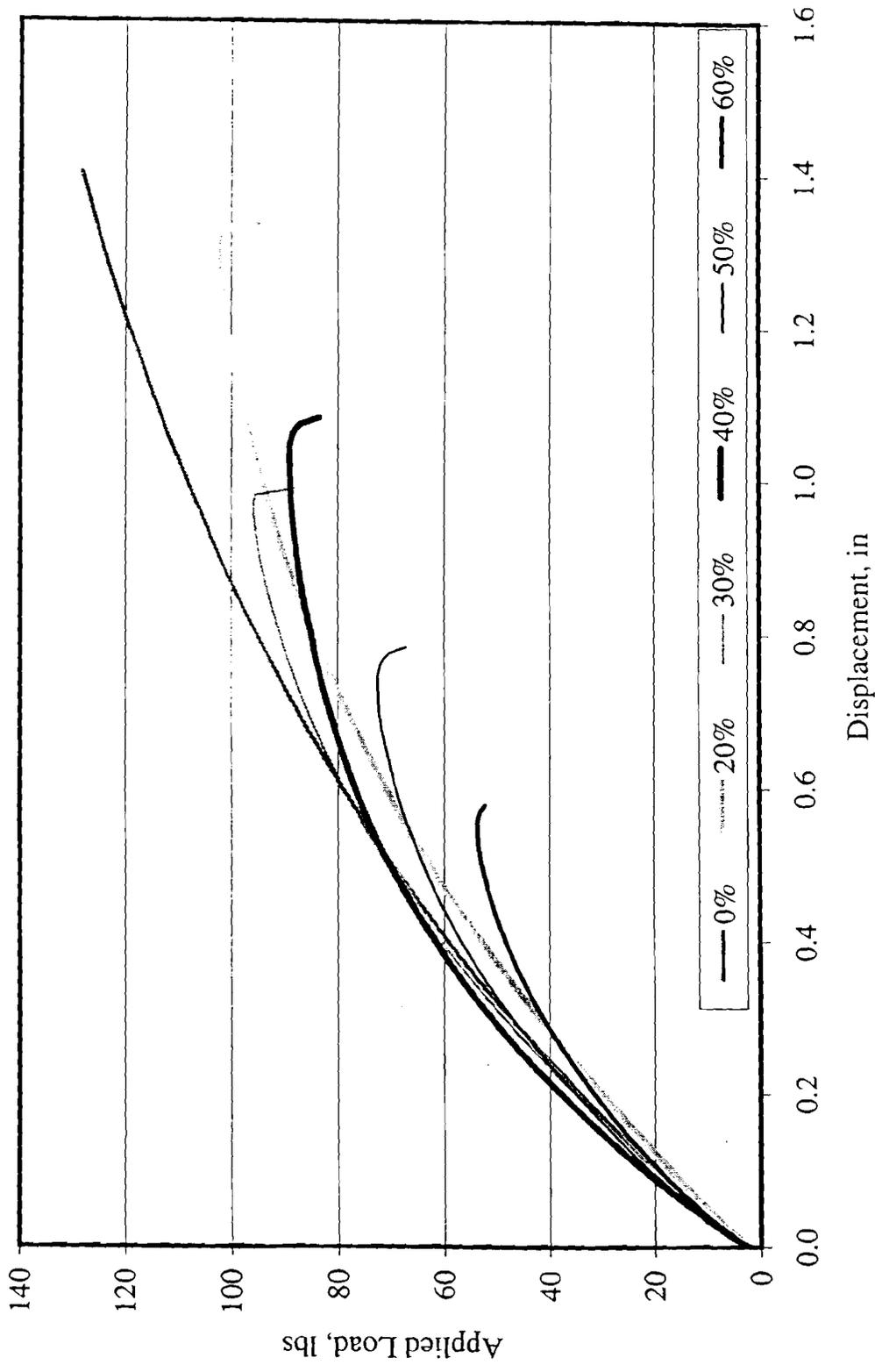
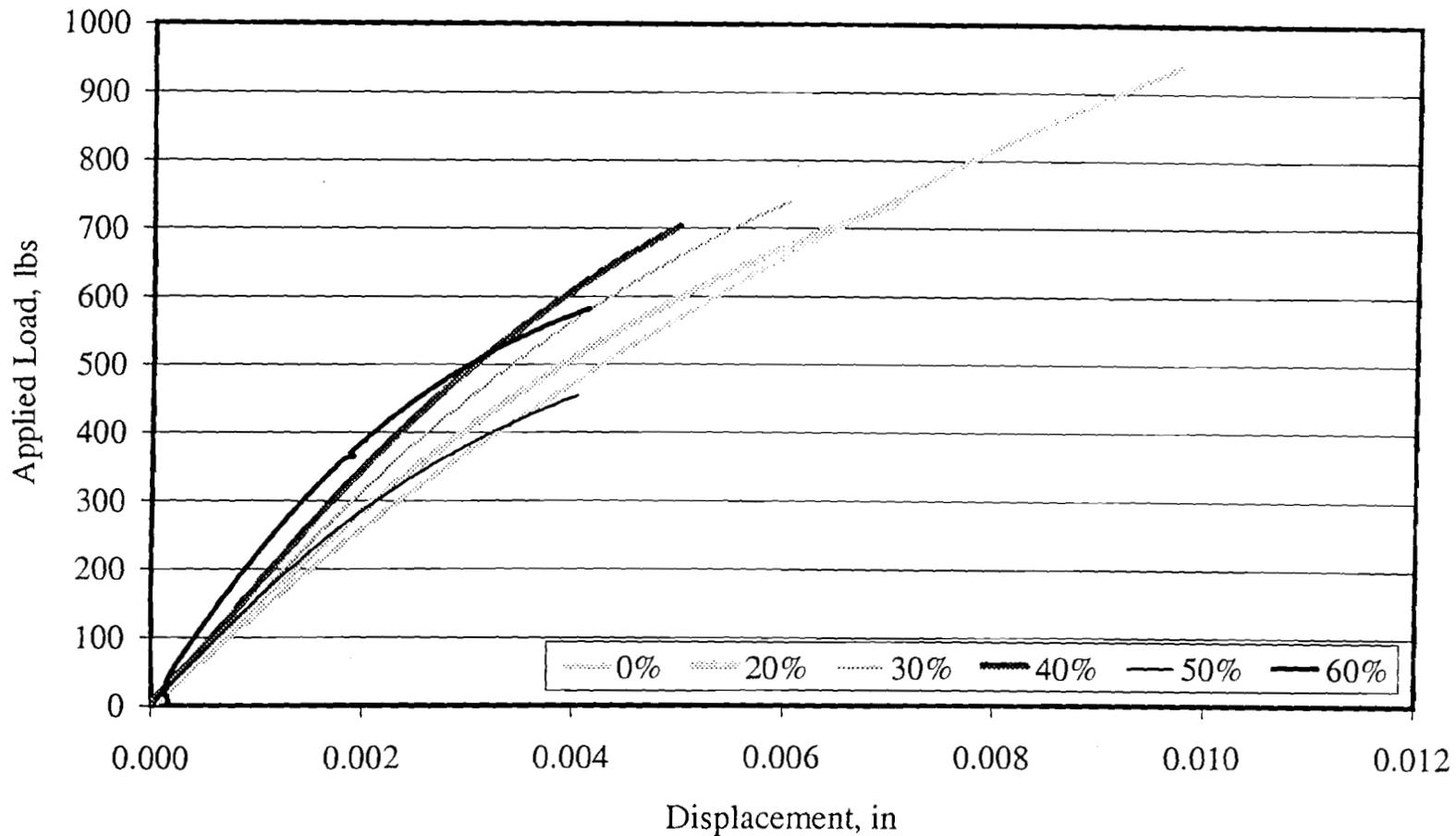
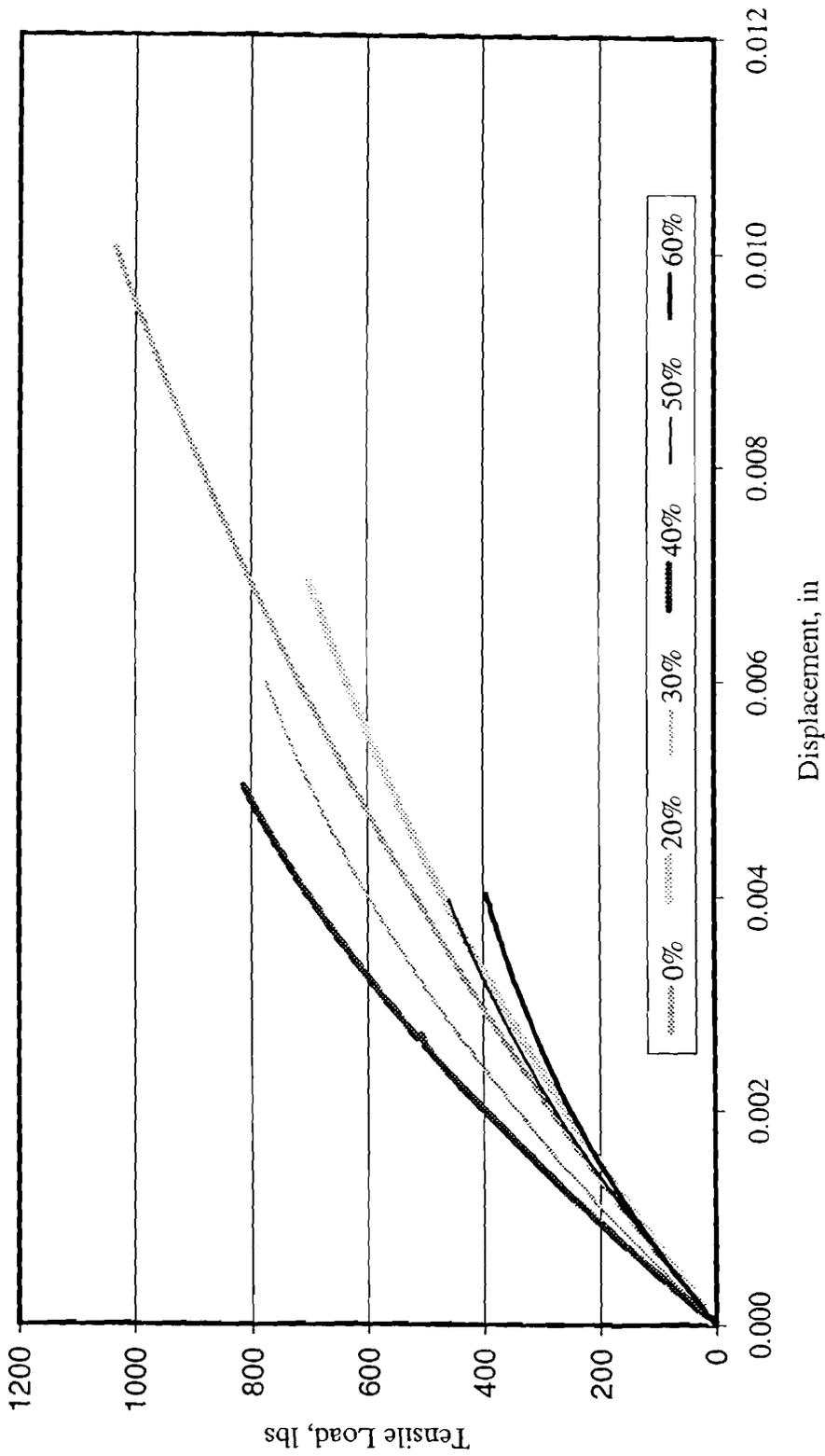


Figure A.2 - Typical Load vs. Displacement Curves for Aged Bending Tests



^aUsed in calculating tensile MOE, the extensometer was removed where the curve ends. Actual tensile loads were higher prior to failure.

Figure A.3 - Typical Load vs. Displacement Curves for the Initial Portion of the Tension Test^a



^aUsed in calculating tensile MOE, the extensometer was removed where the curve ends. Actual tensile loads were higher prior to failure.

Figure A.4 - Typical Load vs. Displacement Curves for Initial Portion of the Aged Tension Test^a

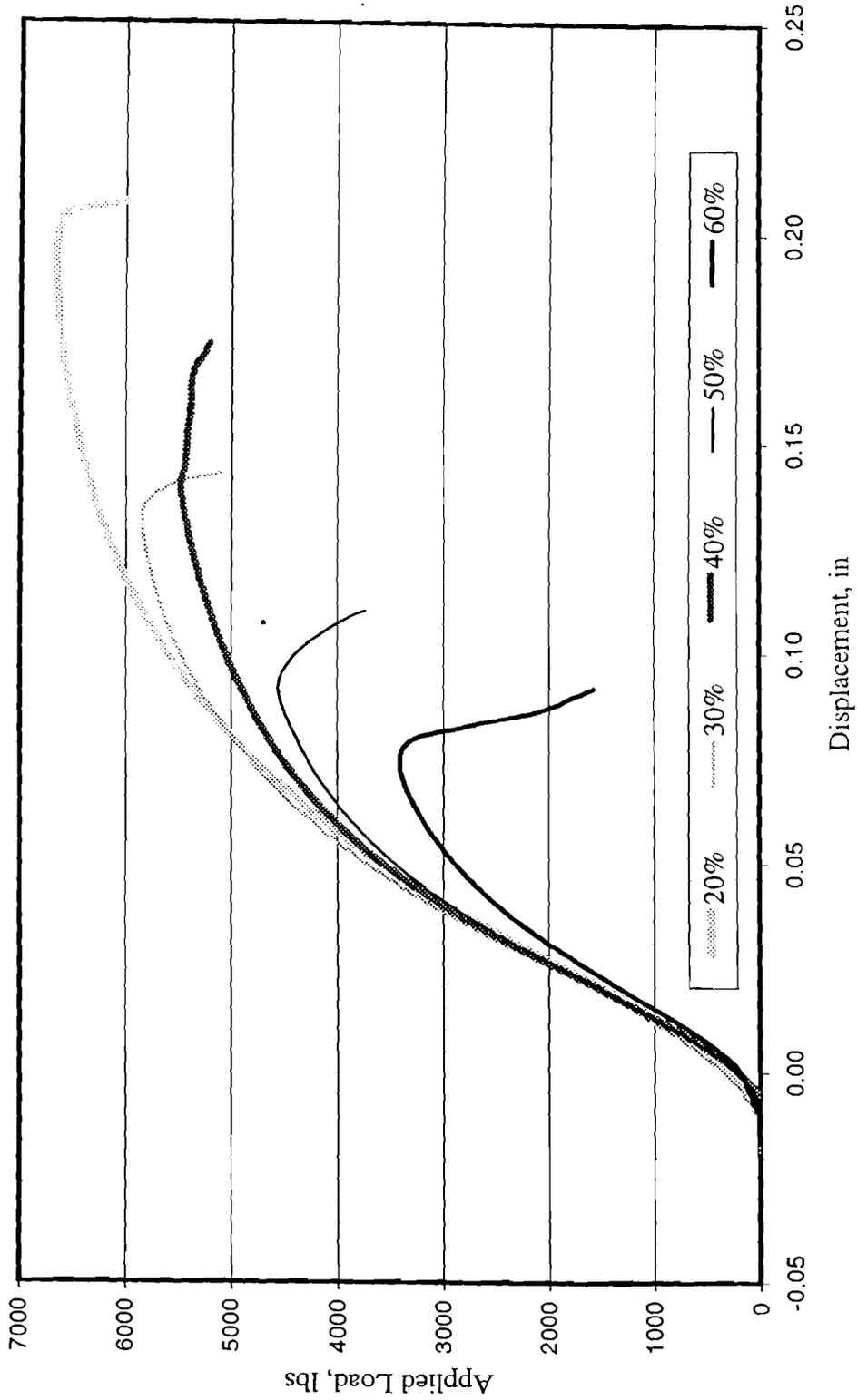


Figure A.5 - Typical Load vs. Displacement Curves for Edgewise Shear Tests

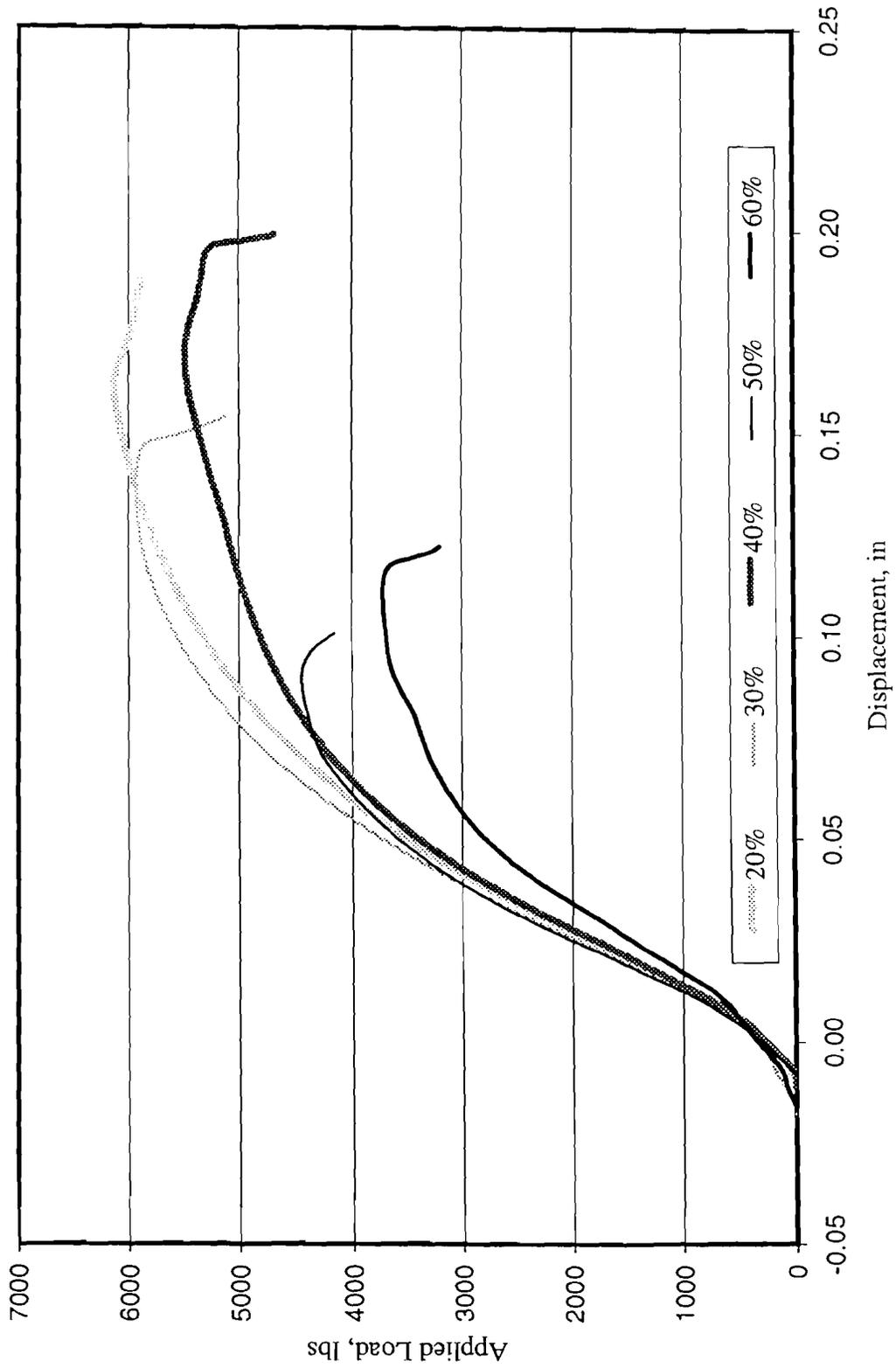


Figure A.6 - Typical Load vs. Displacement Curves for Aged Edgewise Shear Tests

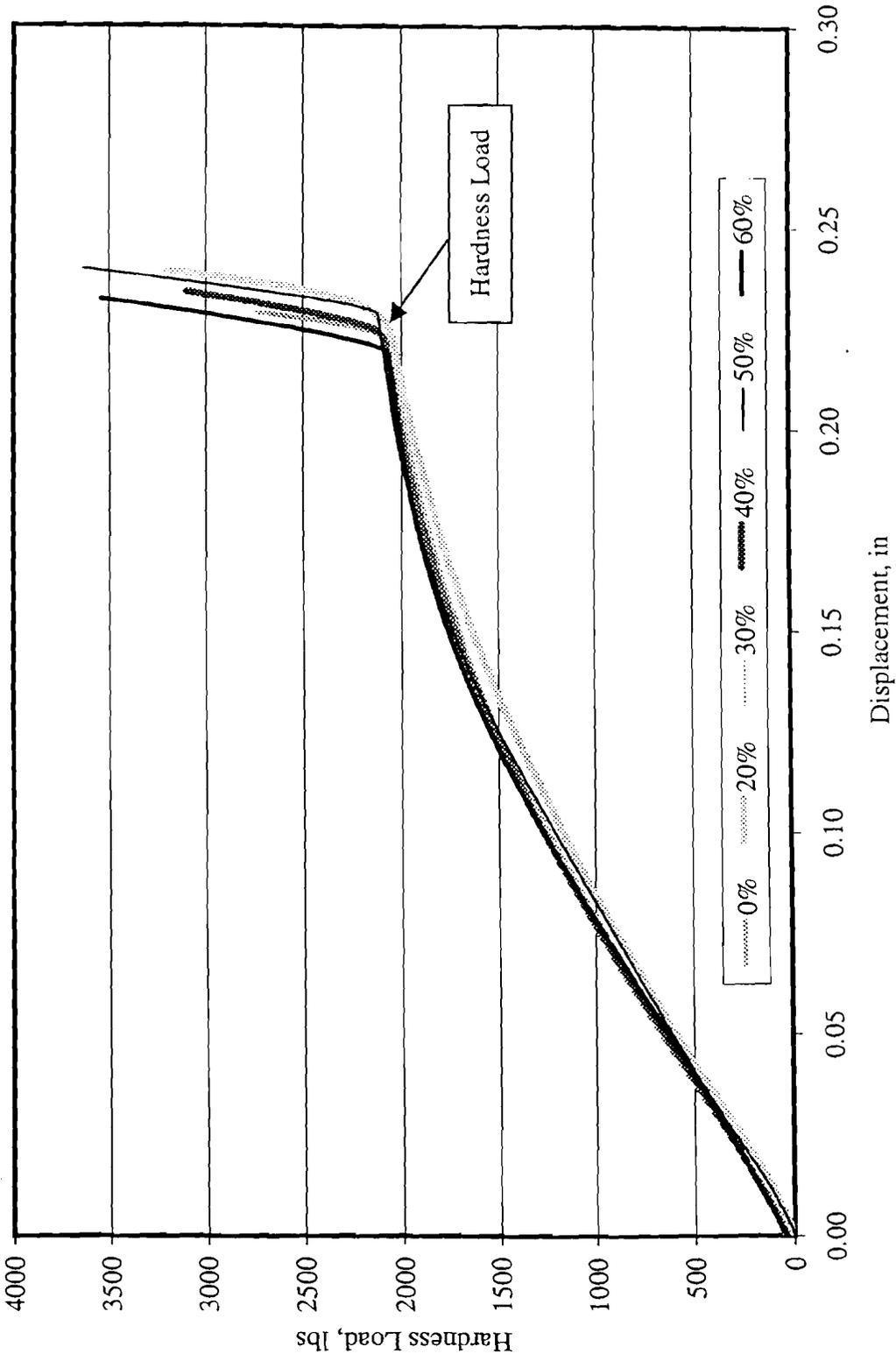


Figure A.7 - Typical Load vs. Displacement Curves for Hardness Test

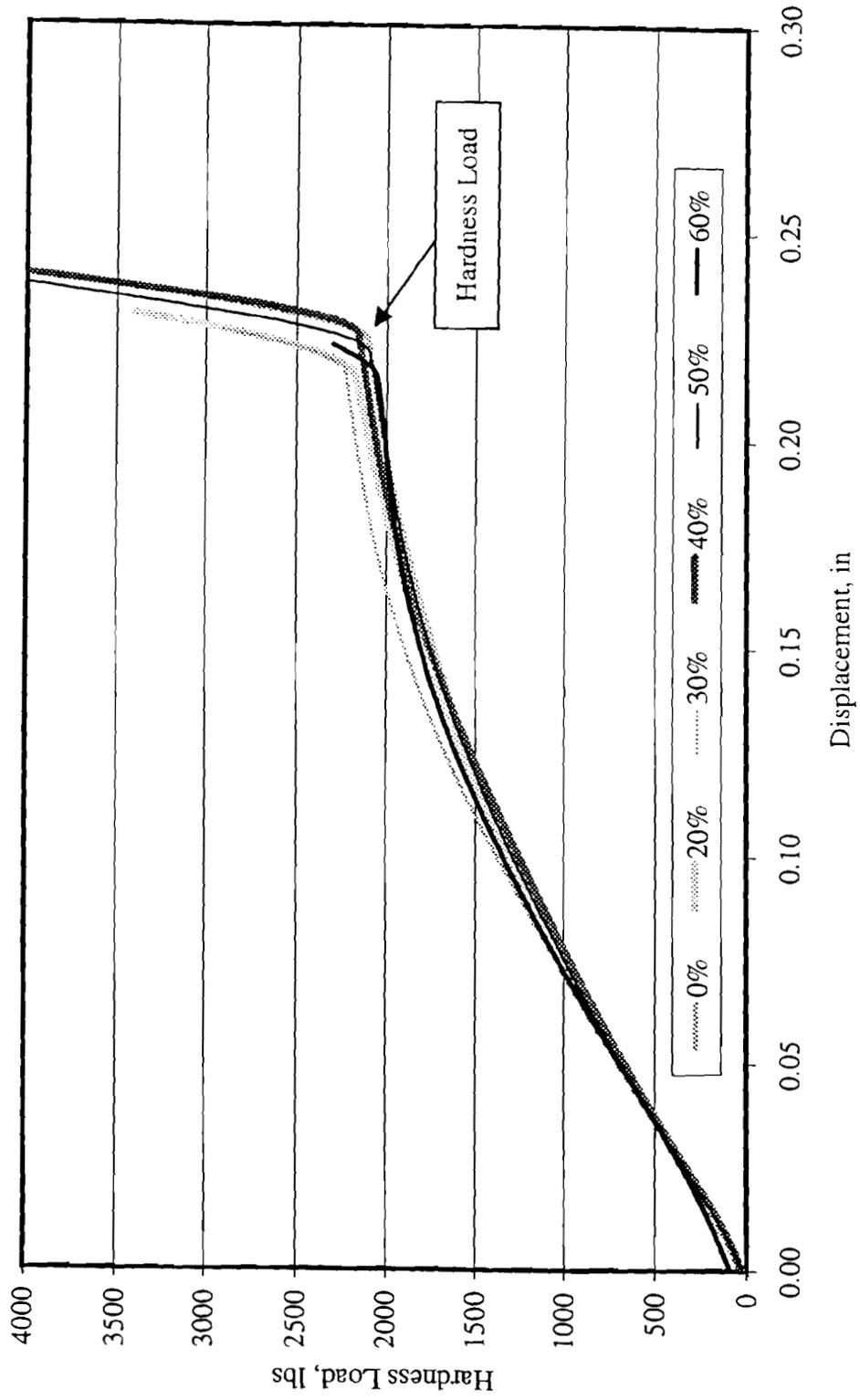


Figure A.8 - Typical Load vs. Displacement Curves for Aged Hardness Tests

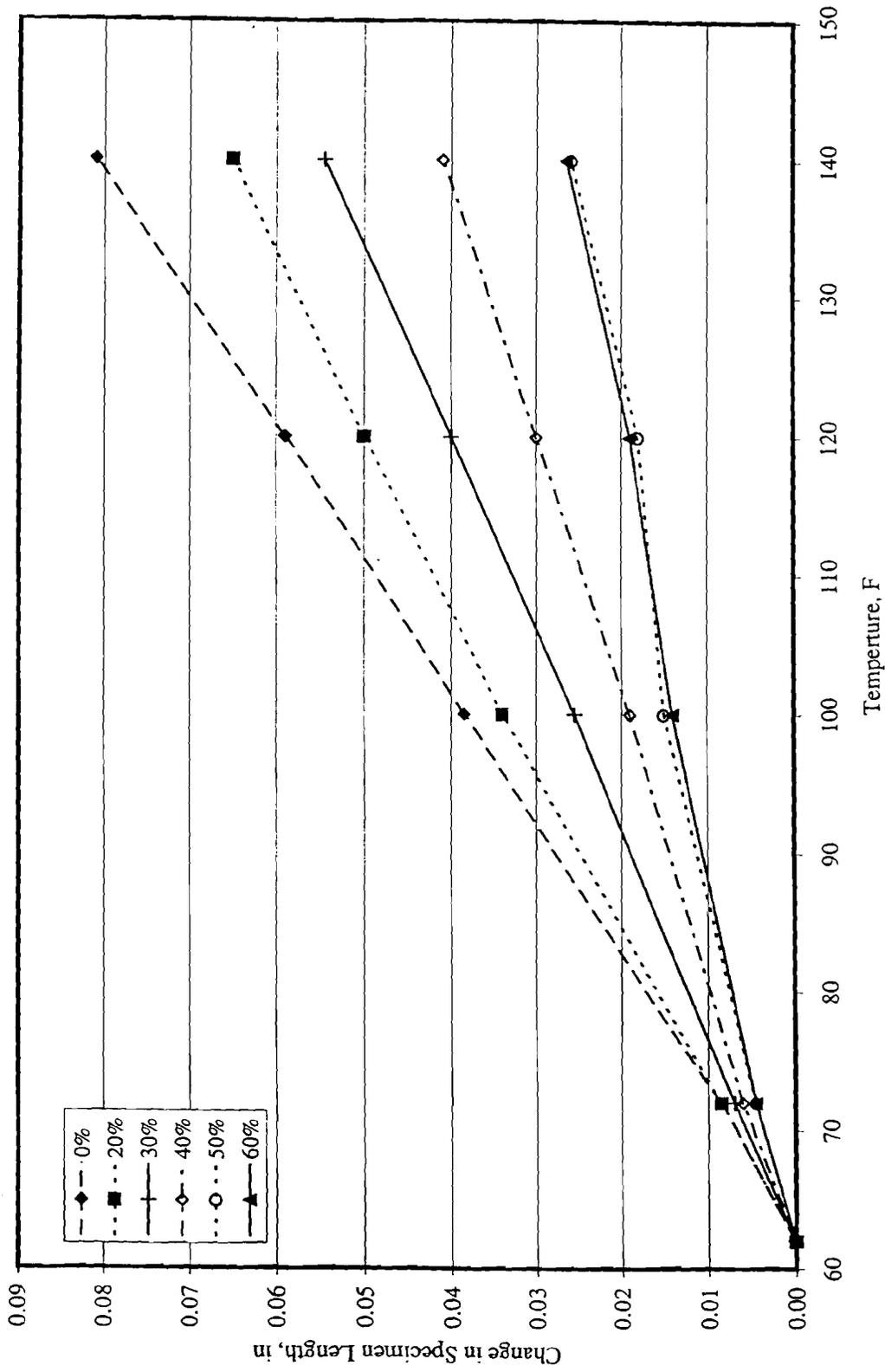


Figure A.9 - Typical Thermal Expansion Curves

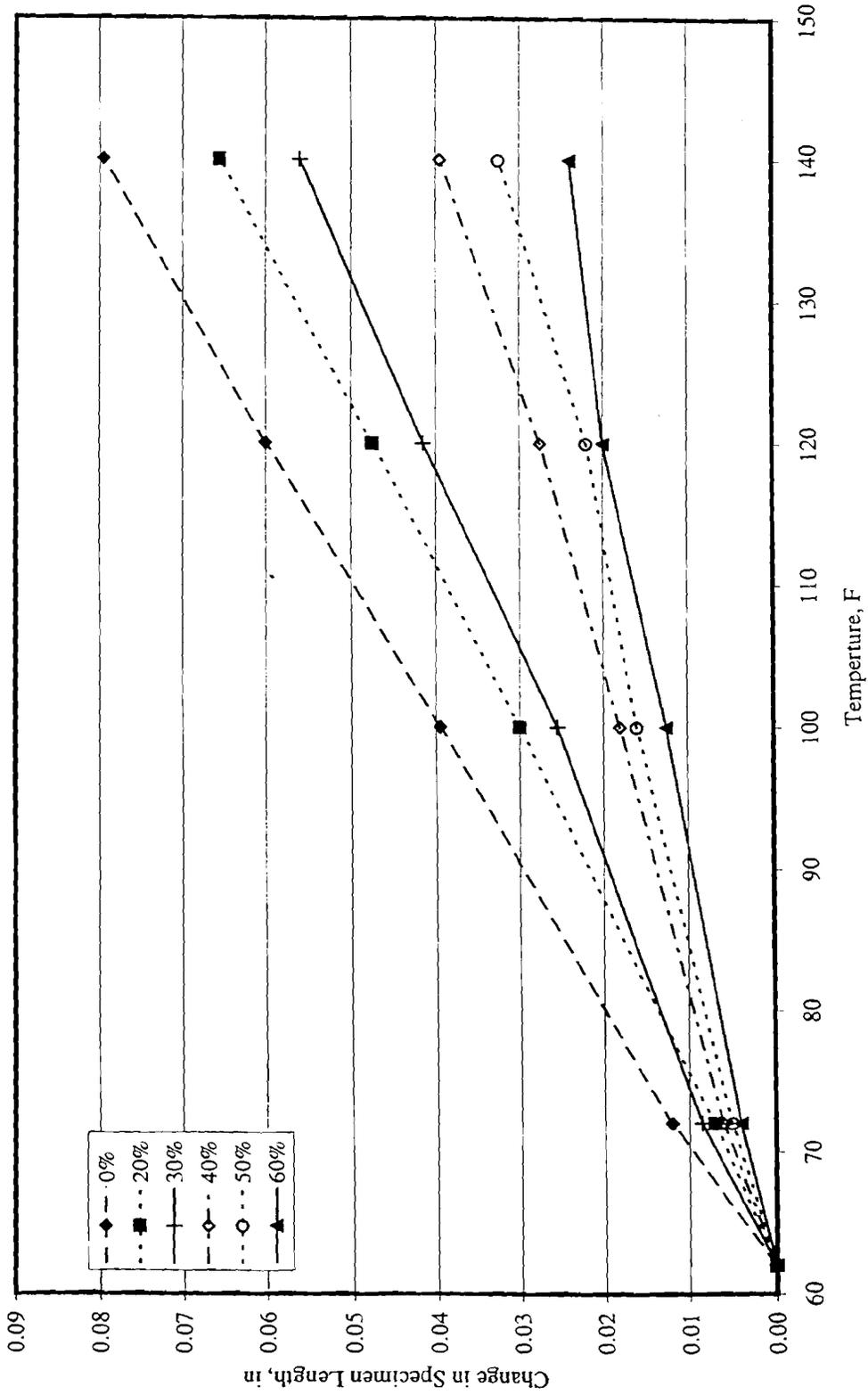


Figure A.10 - Typical Thermal Expansion Curves for Aged Specimens

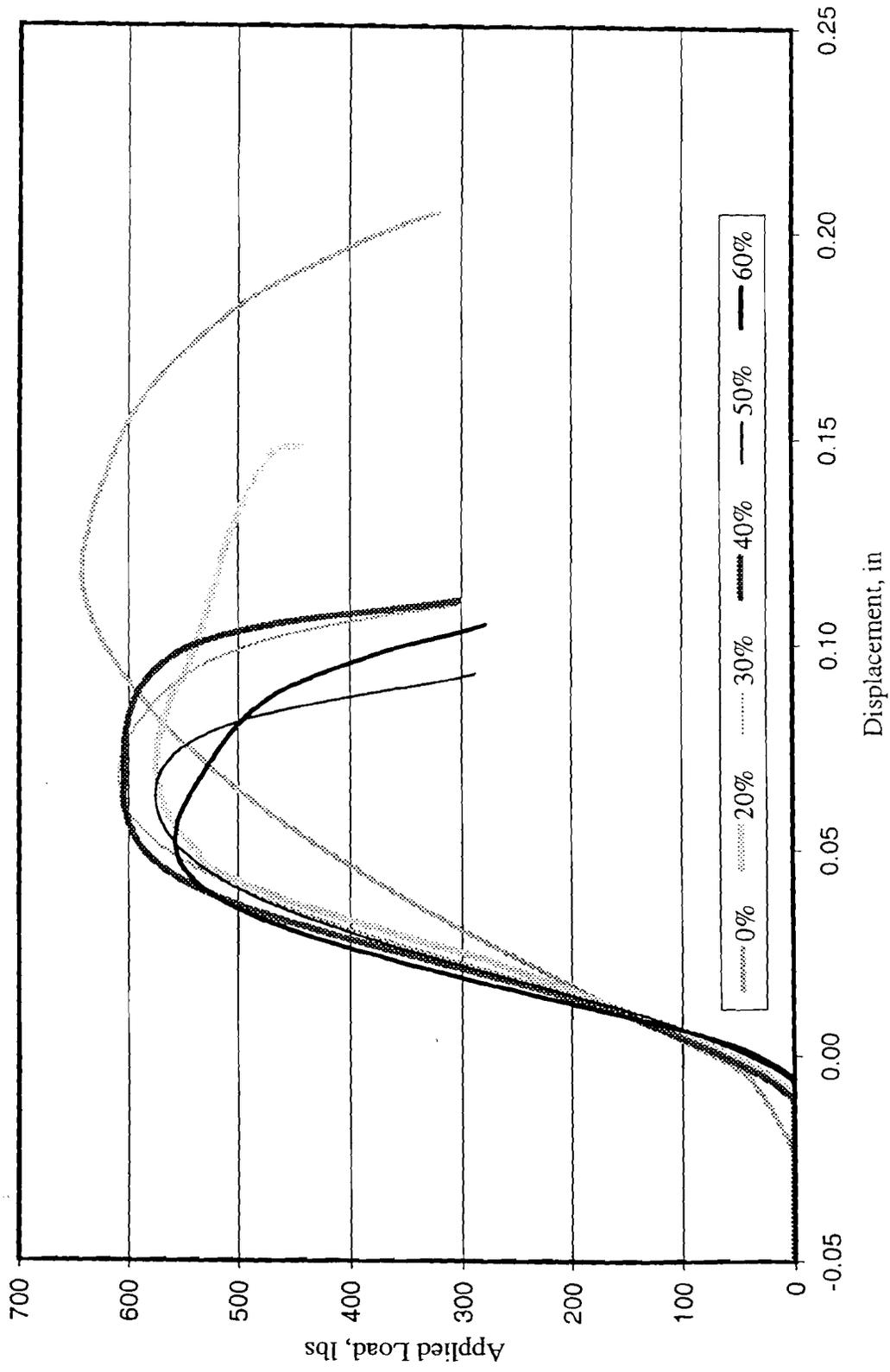


Figure A.11 - Typical Load vs. Displacement Curves for Screw Withdrawal Tests

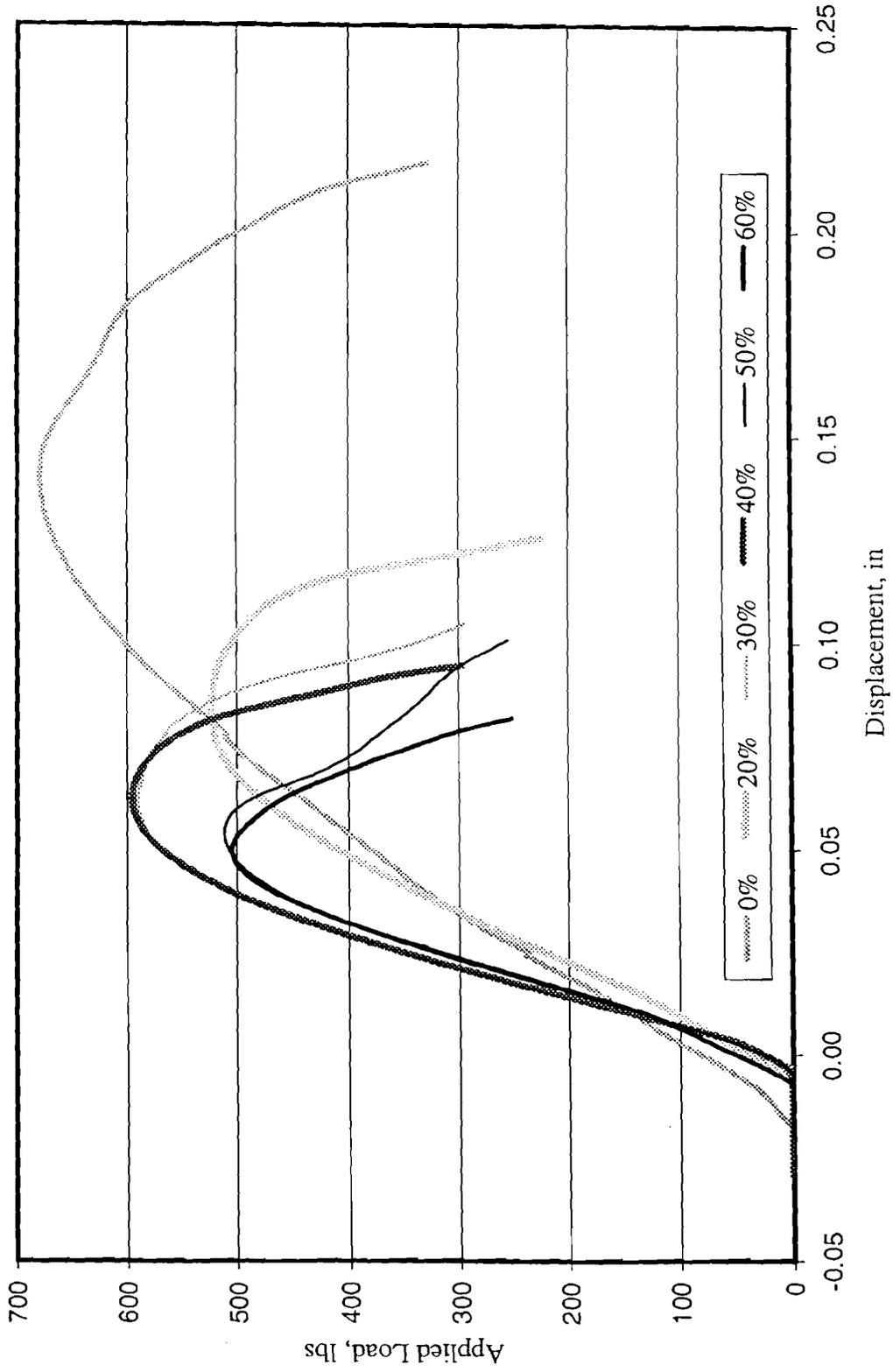


Figure A.12 - Typical Load vs. Displacement Curves for Aged Screw Withdrawal Tests

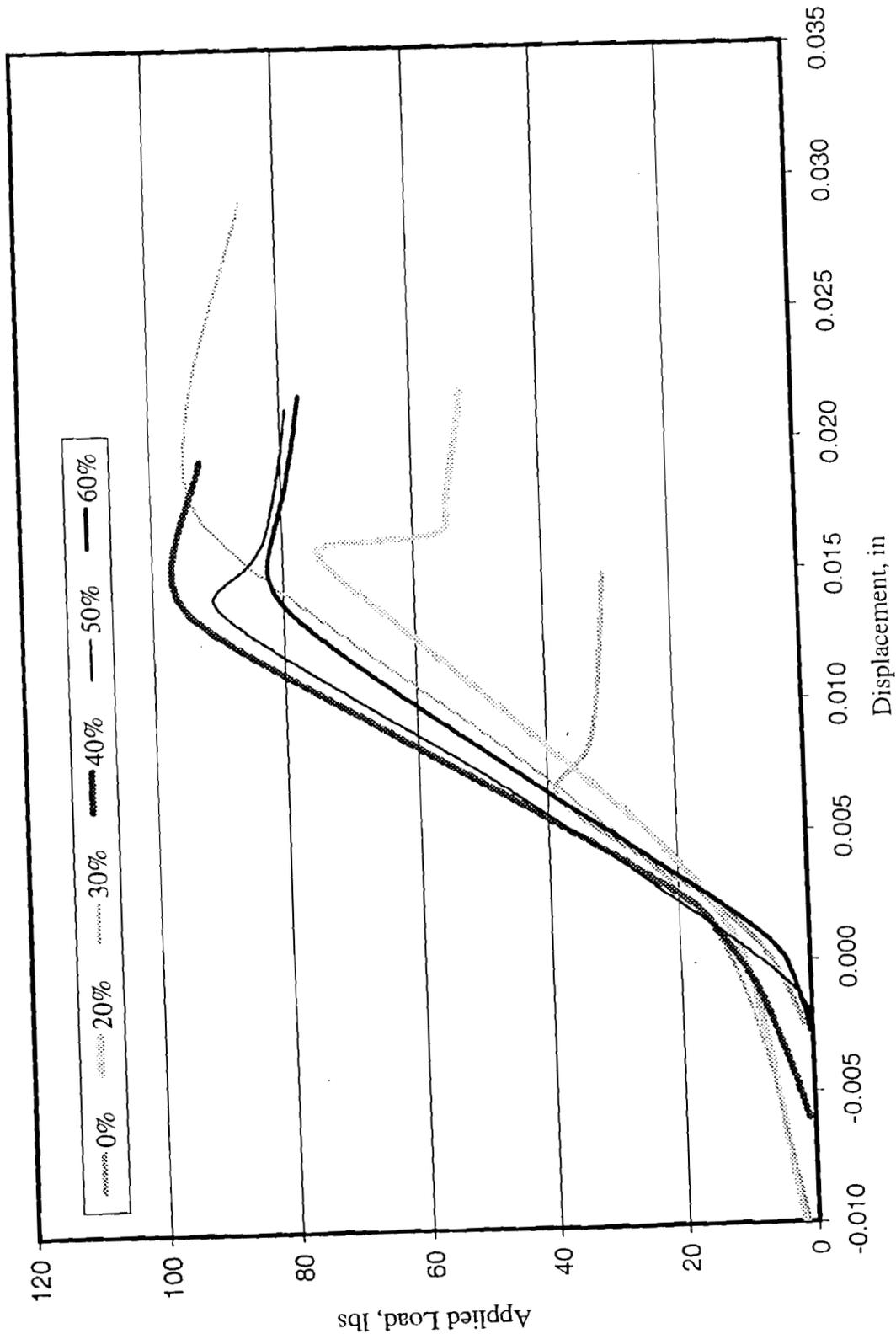


Figure A.13 - Typical Load vs. Displacement Curves for Nail Withdrawal Tests

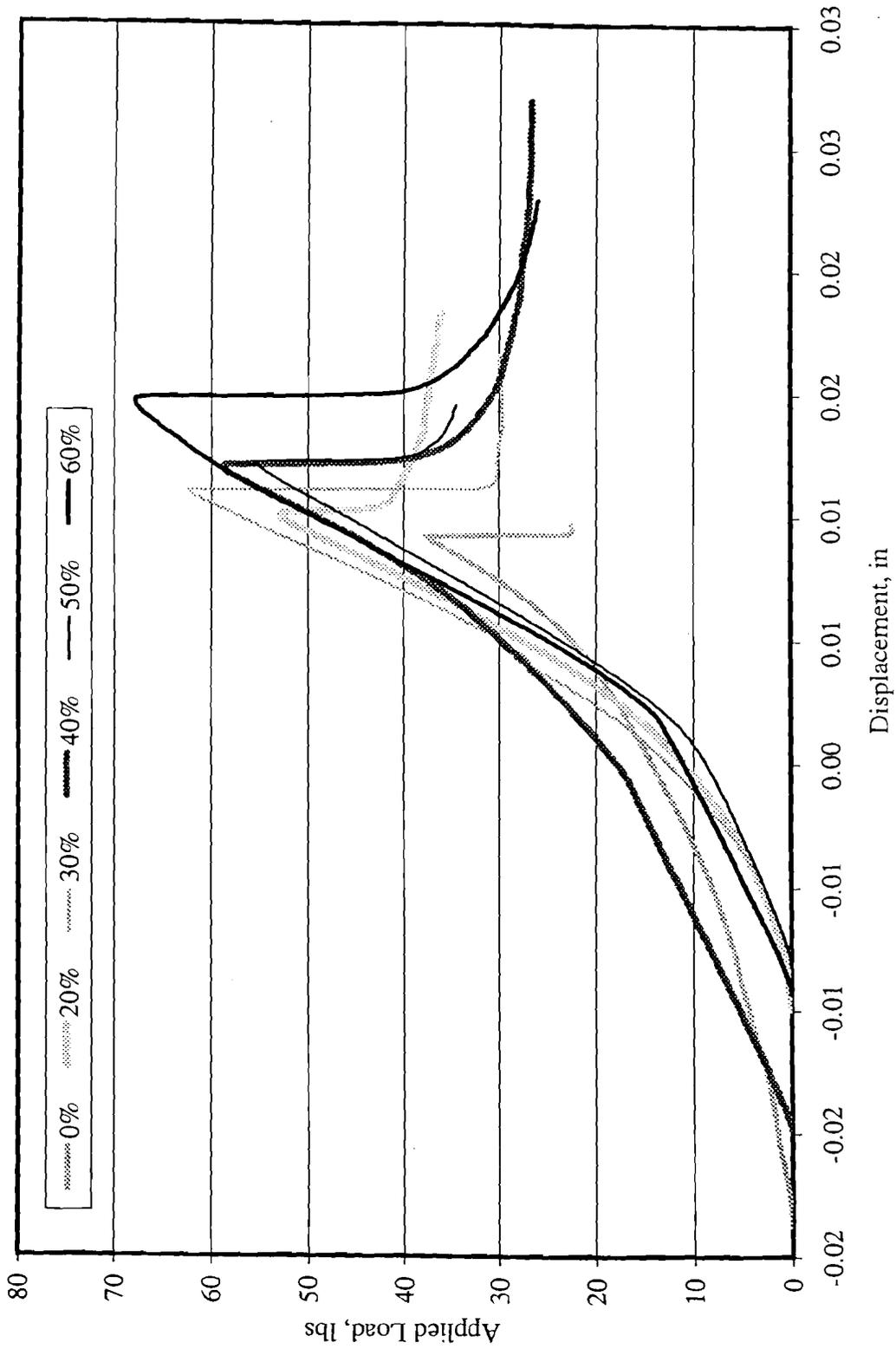


Figure A.14 - Typical Load vs. Displacement Curves for Aged Nail Withdrawal Tests

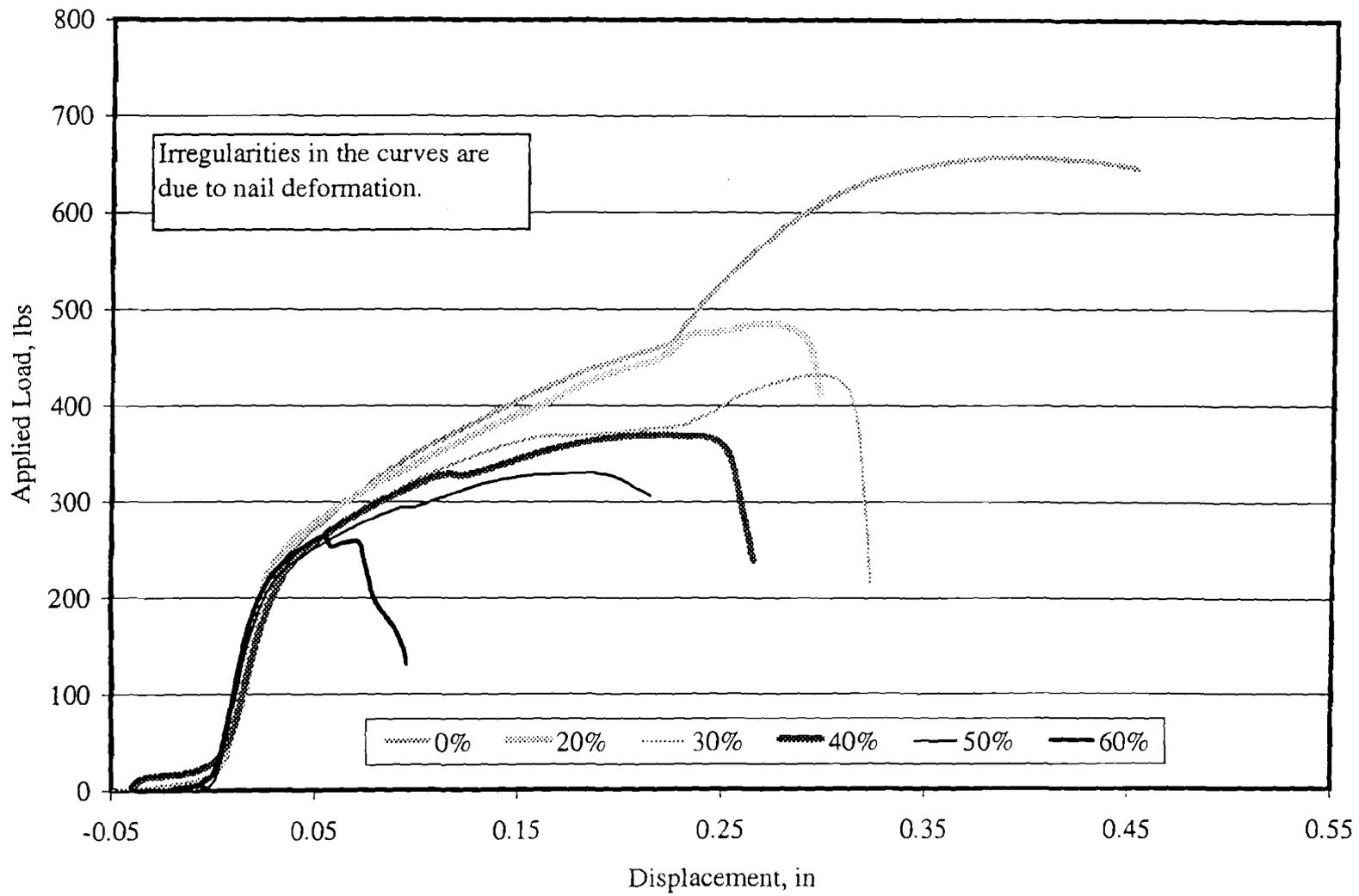


Figure A.15 - Typical Load vs. Displacement Curves for Lateral Nail Resistance Tests

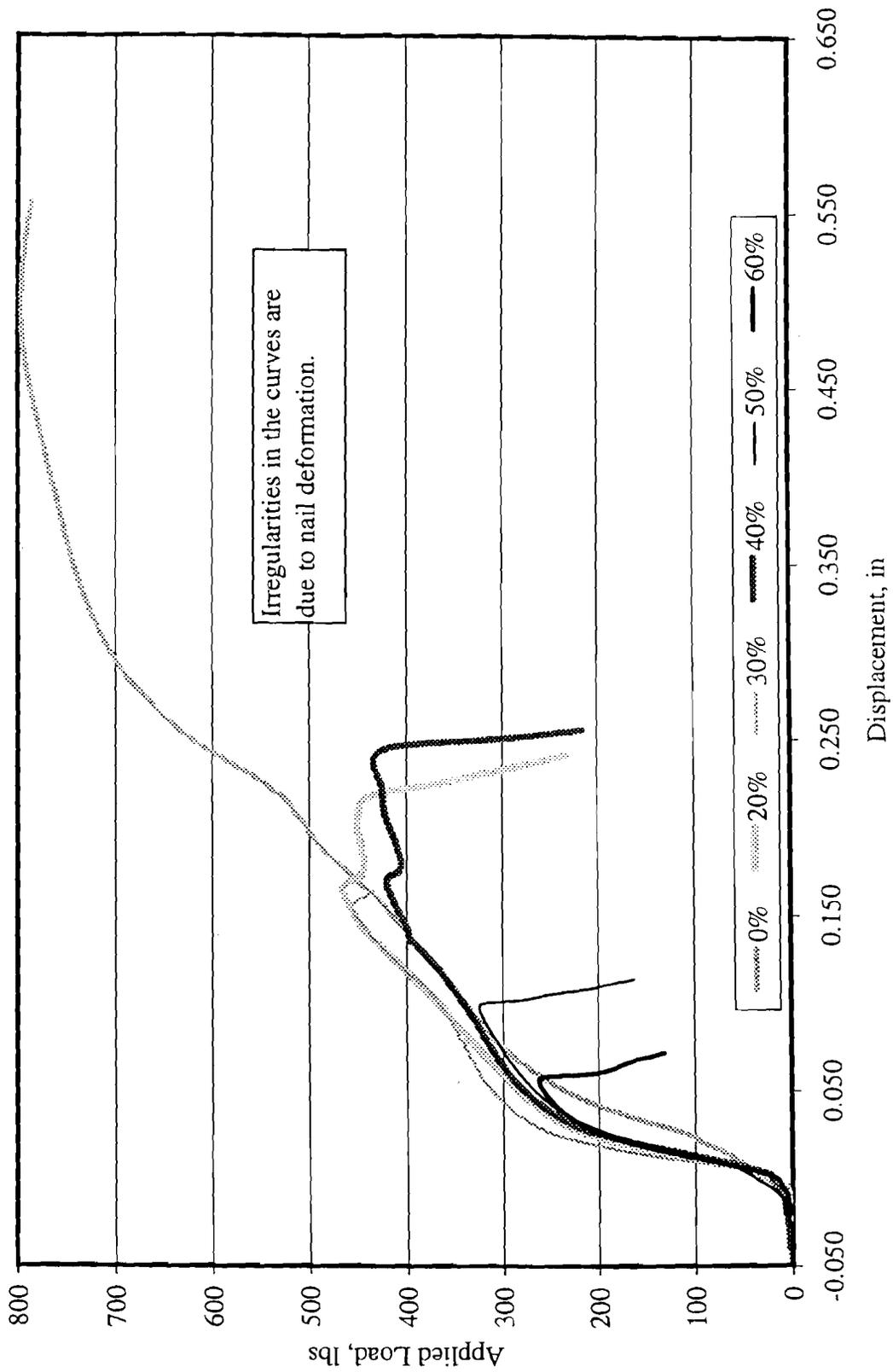


Figure A.16 - Typical Load vs. Displacement Curves for Aged Lateral Nail Resistance Tests

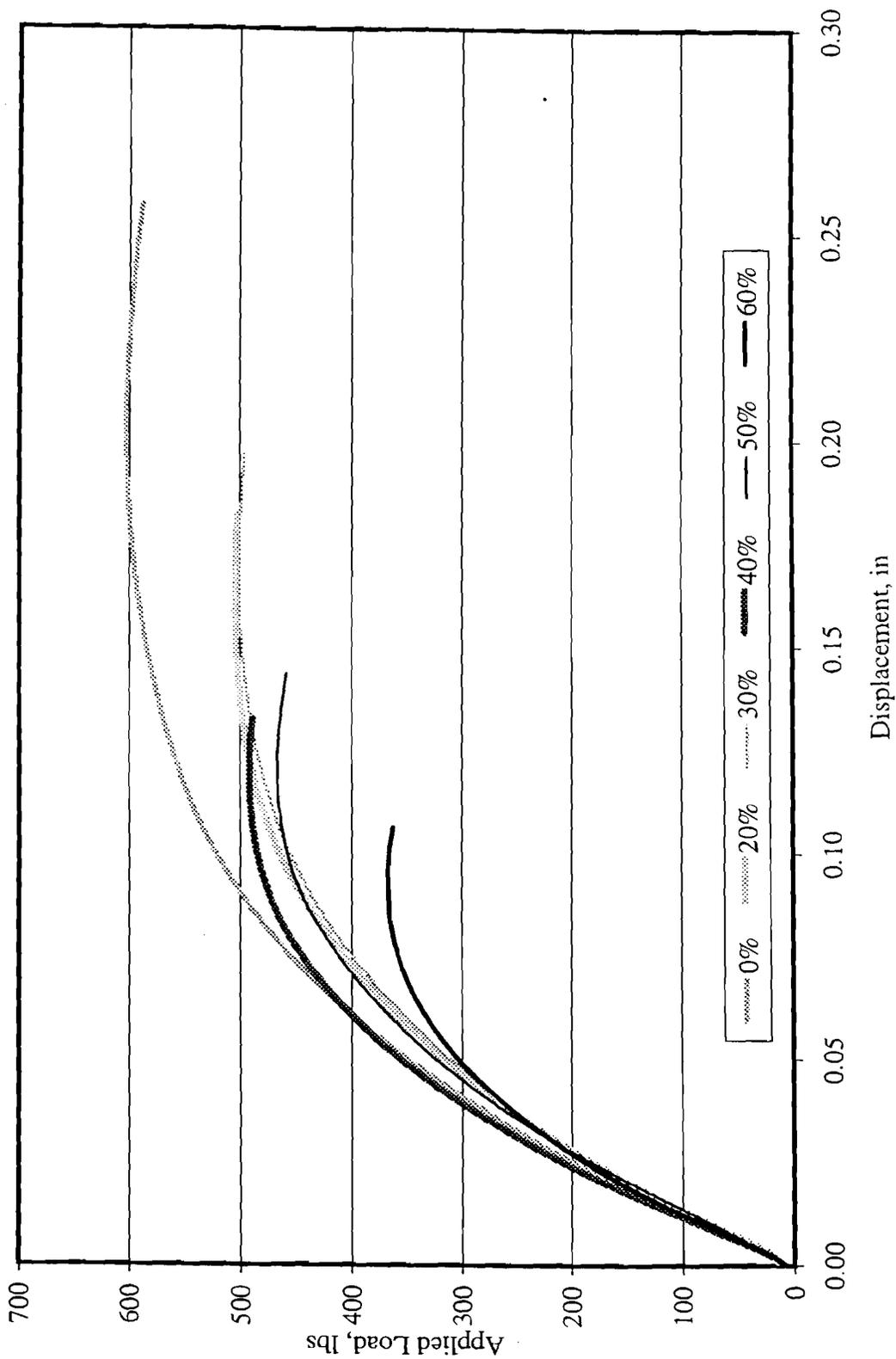


Figure A.17 - Typical Load vs. Displacement Curves for Nail Pull Through Tests

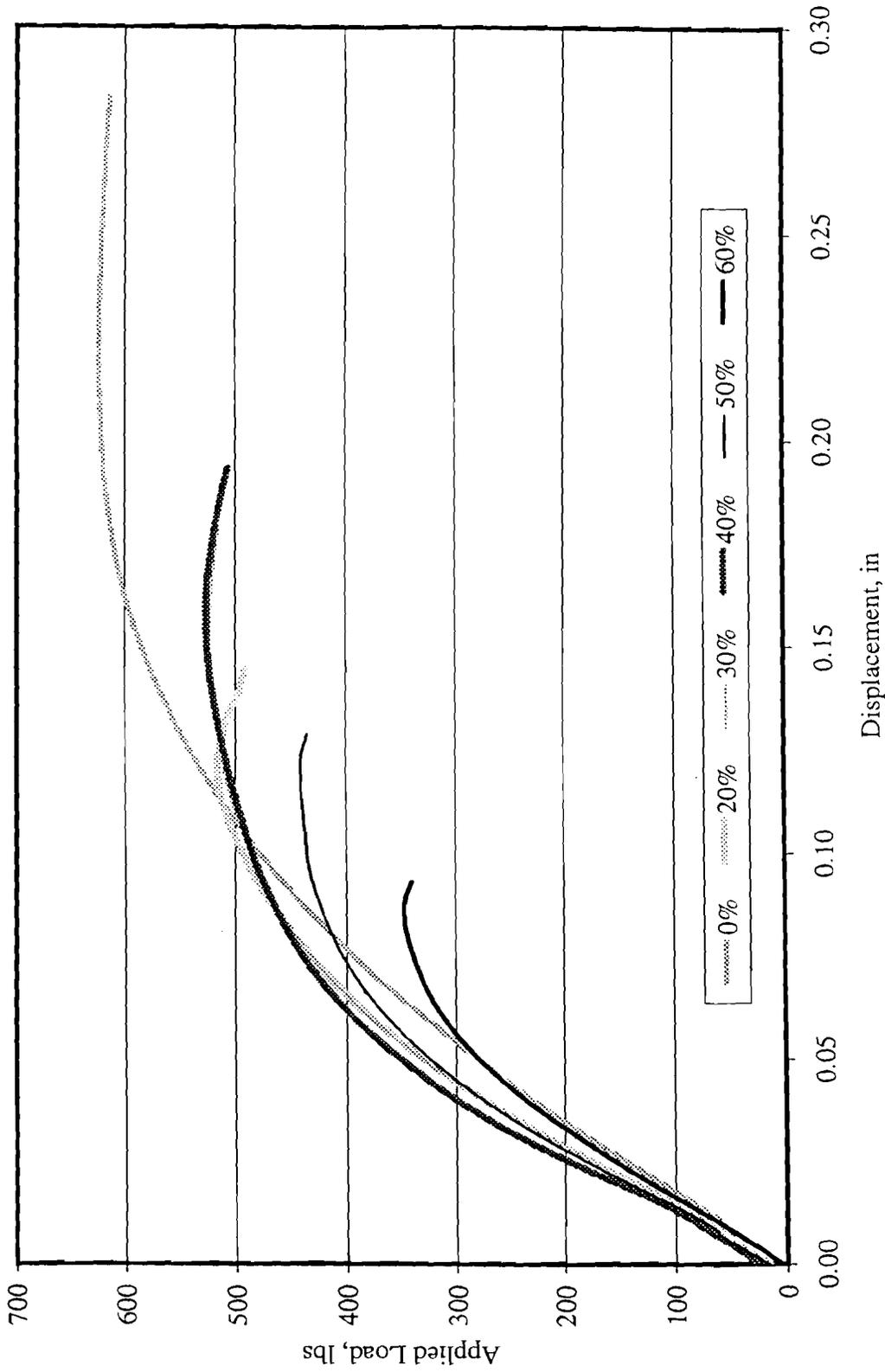
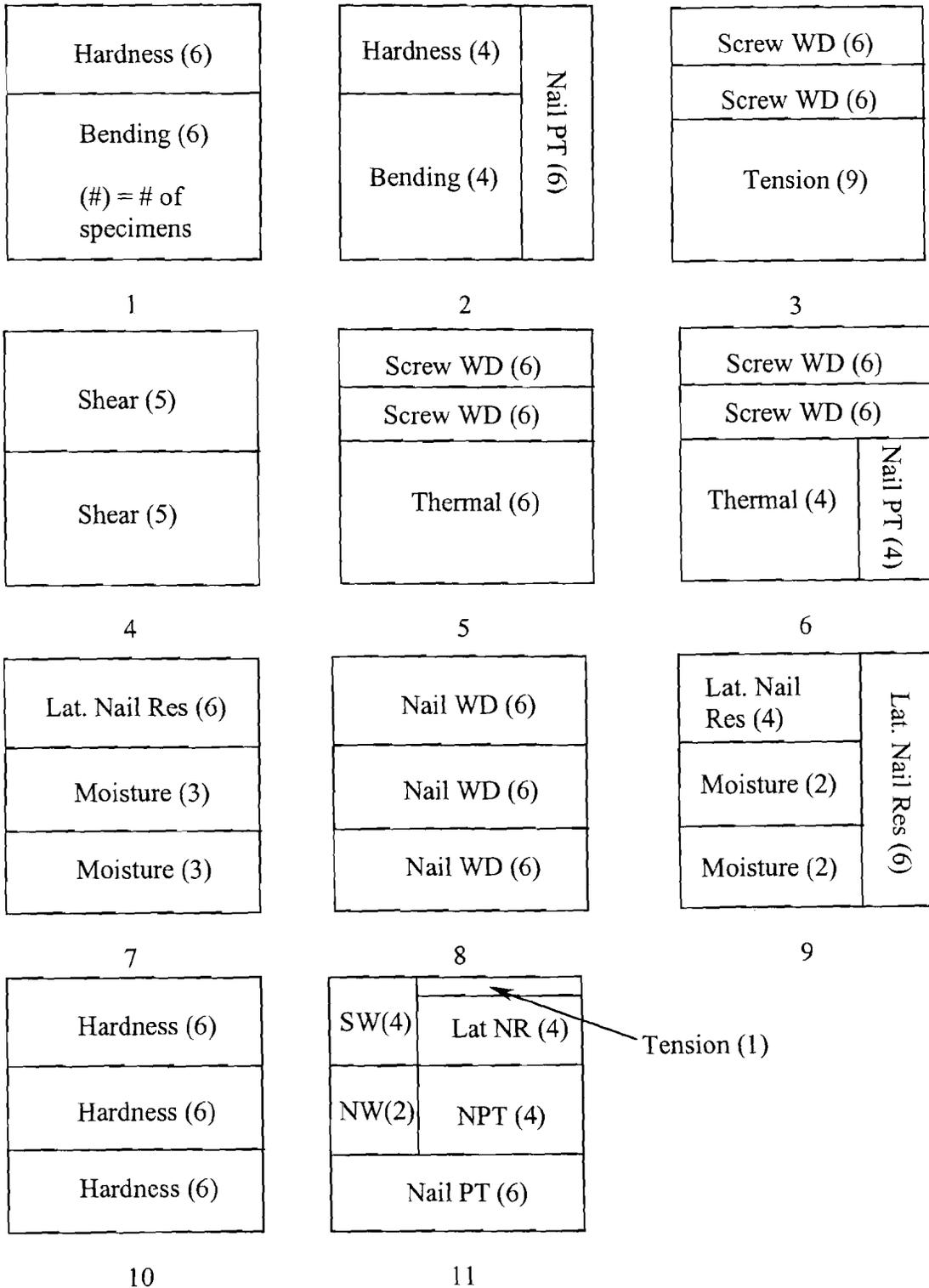


Figure A.18 - Typical Load vs. Displacement Curves for Aged Nail Head Pull Through Tests

Appendix B – Panel Specimen Cutting Schedule

Each panel was approximately 20-in x 20-in. Two sets of the following panels were produced. Aged and Unaged specimens were selected alternately from each panel.



Appendix C - Accelerated Aging Exposure
 Schedule for the Accelerated Aging Test - ASTM D1037

Cycle	Condition	Actual Temp °F/°C	Set Temp °F/°C	Day	Date	Time (Hours)	Start Time	Total Days	Rack Order Top->Bot
1	Water	120/48.9	120/48.9	Mon	6-Apr-98	1	9:15 AM	0	1,2,3,4
1	Steam	200/93.3	193/89.4	Mon	6-Apr-98	3	10:15 AM	0	1,2,3,4
1	Freeze	0/-17.8	NA	Mon	6-Apr-98	20	1:15 PM	0	1,2,3,4
1	Heat	210/98.9	206.6/97	Tues	7-Apr-98	3	9:15 AM	1	1,2,3,4
1	Steam	200/93.3	193/89.4	Tues	7-Apr-98	3	12:15 PM	1	2,3,4,1
1	Heat	210/98.9	206.6/97	Tues	7-Apr-98	18	3:15 PM	1	2,3,4,1
2	Water	120/48.9	120/48.9	Wed	8-Apr-98	1	9:15 AM	2	2,3,4,1
2	Steam	200/93.3	193/89.4	Wed	8-Apr-98	3	10:15 AM	2	2,3,4,1
2	Freeze	0/-17.8	NA	Wed	8-Apr-98	20	1:15 PM	2	3,4,1,2
2	Heat	210/98.9	206.6/97	Thur	9-Apr-98	3	9:15 AM	3	3,4,1,2
2	Steam	200/93.3	193/89.4	Thur	9-Apr-98	3	12:15 PM	3	3,4,1,2
2	Heat	210/98.9	206.6/97	Thur	9-Apr-98	18	3:15 PM	3	4,1,2,3
3	Water	120/48.9	120/48.9	Fri	10-Apr-98	1	9:15 AM	4	4,1,2,3
3	Steam	200/93.3	193/89.4	Fri	10-Apr-98	3	10:15 AM	4	4,1,2,3
3	Freeze	0/-17.8	NA	Fri	10-Apr-98	20	1:15 PM	4	4,1,2,3
	Weekend								
3	Heat	210/98.9	206.6/97	Mon	13-Apr-98	3	12:30 PM	7	1,3,2,4
3	Steam	200/93.3	193/89.4	Mon	13-Apr-98	3	3:30 PM	7	1,3,2,4
3	Heat	210/98.9	206.6/97	Mon	13-Apr-98	18	6:30 PM	7	1,3,2,4
4	Water	120/48.9	120/48.9	Tues	14-Apr-98	1	12:30 PM	8	1,3,2,4
4	Steam	200/93.3	193/89.4	Tues	14-Apr-98	3	1:30 PM	8	1,3,2,4
4	Freeze	0/-17.8	NA	Tues	14-Apr-98	20	4:30 PM	8	3,2,4,1
4	Heat	210/98.9	206.6/97	Wed	15-Apr-98	3	12:30 PM	9	3,2,4,1
4	Steam	200/93.3	193/89.4	Wed	15-Apr-98	3	3:30 PM	9	3,2,4,1
4	Heat	210/98.9	206.6/97	Wed	15-Apr-98	18	6:30 PM	9	2,4,1,3
5	Water	120/48.9	120/48.9	Thur	16-Apr-98	1	12:30 PM	10	2,4,1,3
5	Steam	200/93.3	193/89.4	Thur	16-Apr-98	3	1:30 PM	10	2,4,1,3
5	Freeze	0/-17.8	NA	Thur	16-Apr-98	20	4:30 PM	10	2,4,1,3
	Weekend								
5	Heat	210/98.9	206.6/97	Mon	20-Apr-98	3	10:30 AM	14	4,1,3,2
5	Steam	200/93.3	193/89.4	Mon	20-Apr-98	3	1:30 PM	14	4,1,3,2
5	Heat	210/98.9	206.6/97	Mon	20-Apr-98	18	4:30 PM	14	4,1,3,2
6	Water	120/48.9	120/48.9	Tues	21-Apr-98	1	10:30 AM	15	3,4,1,2
6	Steam	200/93.3	193/89.4	Tues	21-Apr-98	3	11:30 AM	15	3,4,1,2
6	Freeze	0/-17.8	NA	Tues	21-Apr-98	20	2:30 PM	15	3,4,1,2
6	Heat	210/98.9	206.6/97	Wed	22-Apr-98	3	10:30 AM	16	3,4,1,2
6	Steam	200/93.3	193/89.4	Wed	22-Apr-98	3	1:30 PM	16	1,4,3,2
6	Heat	210/98.9	206.6/97	Wed	22-Apr-98	18	4:30 PM	16	1,4,3,2
7	Conditioning	68/20	NA	Thur	23-Apr-98	48	10:30 AM	17	NA
	Weekend								
Completion of Accel. Aging				Sat	25-Apr-98	336	10:30 AM	19	

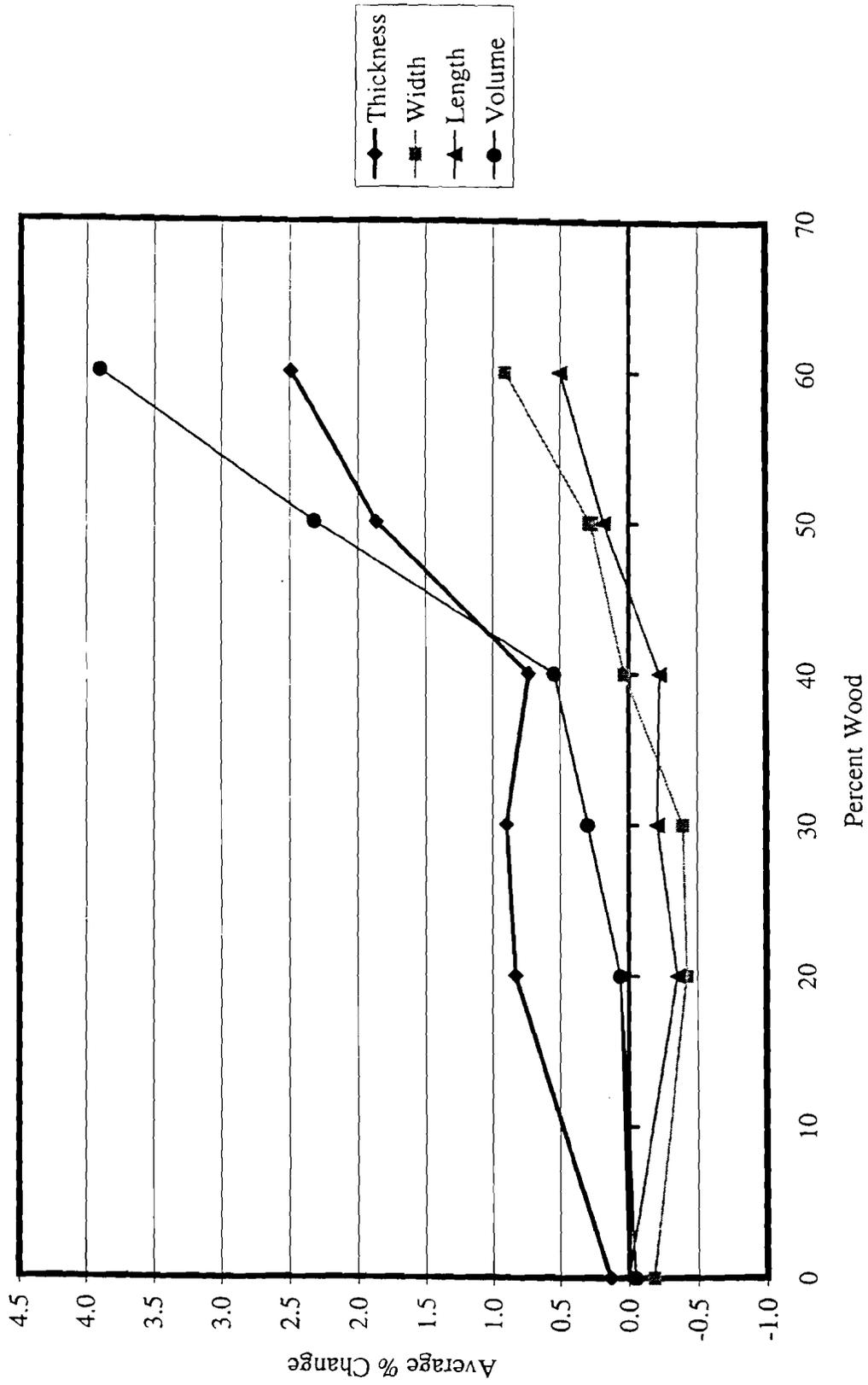


Figure C.1 - Permanent Thickness Swell Resulting from Accelerated Aging Exposure.

Appendix D – Calculating the Slope of Nonlinear Curves

As shown in Appendix A, some of the load vs. displacement curves do not contain a linear portion for calculating the MOE. Therefore, a nonlinear approximation was used to find the initial slope of the curve. A computer program, developed by Joe Murphy at the FPL, uses a nonlinear least squares fit to estimate four parameters of a hyperbolic tangent curve. The equation for this curve is:

$$P = c_1 \tanh(c_2(x - c_4)) + (x - c_4) \quad (D1)$$

where: P = Load;

x = displacement;

c₁ = parameter 1 based on c₃ and c₄;

c₂ = parameter 2 based on c₁ and c₃;

c₃ = slope of the ending portion of the curve; and

c₄ = x intercept.

The slope of this curve at any point x can be found by taking the derivative of P with respect to x resulting as:

$$\frac{dP}{dx} = c_1 \cdot c_2 \operatorname{sech}^2(c_2(x - c_4)) + c_3 \quad (D2)$$

The initial slope occurs at the x intercept or c₄. Substituting this into the above equation gives:

$$\frac{dP}{dx} = c_1 \cdot c_2 + c_3 \quad (D3)$$

Testworks® is a windows program written by Sintech/MTS[™] Systems for testing machine control, data collection, and data analysis. Version 3.07 was used in this study.

Testworks® calculates the slope of the data by finding the primary slope of the beginning portion of the curve. This slope is then converted to MOE values by applying the geometric properties of the material.