ALASKAN TIMBER RESOURCES FOR WOOD-PLASTIC COMPOSITES

By

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ALASKAN TIMBER RESOURCES FOR WOOD-PLASTIC COMPOSITES

ABSTRACT

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The goal of this study was to develop and demonstrate that commercially viable wood plastic composite products can be produced using two separate Alaskan low-value waste streams from secondary industry and woody biomass from urban wood waste lots (birch and woody biomass material (WBM)). Because of the harsh environmental exposures such products would experience in Alaska, further understanding of how environmental exposure influences mechanical properties, as well as their viscoelastic response, was also investigated. Particle size analysis of raw materials indicated a wider particle size distribution in birch and especially WBM samples relative to pine control specimens. Statistically lower diffusion coefficients associated with Alaskan material were also found during water soak testing. However, mechanical testing of specimens found no statistical difference in flexural strength, stiffness, creep recovery, or fastener withdrawal tests between any of the feedstock types. As a result, WPCs made with the two Alaskan low-value woody materials should be considered a viable option for the Alaskan forest products industry. Static flexure results indicated a significant influence of weathering with ultra violet light and freeze thaw cycling of specimens upon values of strength, stiffness, and strain to failure. It also appeared the coupled weathering created larger influences upon flexural properties than independent weathering. However, results suggest that freeze-thaw cycling had a significantly larger affect than UV exposure. Weathering of WPC caused significant increases in flexural creep strain as well, especially within the first minute of

sustained loading. This is believed to occur as a result of the large influence weathering has upon static response of composites. Consequently, increases in creep strain after one minute and creep strain rates from weathering were not found to be statistically significant. Although not statistically significant, coupled weathering of specimens appeared to have a larger influence upon creep strains than independent weathering with freeze-thaw cycling and UV exposure.

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CHAPTER ONE: INTRODUCTION

INTRODUCTION

In recent years, the Alaskan forest products industry has suffered considerably with mill closures, tougher environmental regulations, and a decline in demand from Pacific-rim countries, previously Alaska's primary export market (Braden et al 2000). Measured by revenue brought into the state, the forest products industry has declined from 5% of the states economic base in 1965, to 2.3% in 1985, to less than 1% today (Kenworthy 2000). However, there has been an increase in number of secondary manufacturing operations such as furniture and cabinet manufacturers, indicating a general interest in building secondary forest products sector (Braden et al 2000).

The use of low-value woody materials in secondary manufacturing operations, such as wood-plastic composites (WPC), has been researched and found viable in multiple studies (Ashori et al. 2008; Kamdem et al. 2004; Peterson 2008; Stark 1999; Youngquist et al. 1995). Sources of recycled feedstock have been quite varied in studies, ranging from recycled newspapers (Ashori et al. 2008; Youngquist et al. 1995) to scrap pallets (Stark 1999), to CCA treated wood removed from service (Kamden et al. 2003). Regardless of the source, most studies have found composites comprised of these materials to produce acceptable physical/mechanical properties and possess distinctive characteristics. WPCs produced with wood fiber derived from scrap pallets and crates have shown greater strength and decreased percentages of shrinkage in laboratory testing when compared to commercially available pine wood flour (Stark 1999). Compression molded panels comprised of CCA-treated lumber showed increases in strength and stiffness properties, as well as a greater resistance to photodegradation and fungal decay

compared to non-treated lumber (Kamdem et al. 2004). Also, recycled newspapers used as composite reinforcing filler were found to provide better physical/mechanical properties than wood flour (Ashori et al. 2008; Youngquist et al. 1995).

With an ever increasing market share in the forest products industry, the WPC industry certainly exhibits potential to facilitate the use of low-value woody material in a profitable sense for Alaska. As the market share for the use of pressure treated lumber in residential decking applications declines, a stark increase in demand for WPC decking has been seen. The WPC share of the North American decking market has grown substantially in recent years, with demand forecasted to rise 9.5 percent per year through 2013 (Freedonia 2009).

WPCs, as used in decking applications, are often marketed as having little to no maintenance through its life cycle and being very durable in outdoor applications. Relatively speaking, this is true when compared to standard decking lumber, but research has shown that considerable quality deterioration does occur when WPC products are exposed to environmental conditions such as ultra violet light, moisture, and freezing (Kiguchi et al 2006; Stark 2001; Panthapulakkal et al 2006; Pandey et al 2008; Pandey 2005). Strength and stiffness properties have been shown in laboratory testing to diminish with such exposures, but very little research has been conducted on the effects of coupled environmental exposures to strength and stiffness. Coupled environmental exposure could be seen as a more realistic testing approach, considering decking material often experiences more than one type of environmental exposure simultaneously (i.e. moisture, temperature, irradiation, etc.)

Also, almost no research has been conducted on the effect environmental exposure has on the viscoelastic response of WPCs. Viscoelastic response is an important aspect to consider with WPC decking because a product that can sustain its performance level over a greater amount of

time is going to be a more marketable product. Since it has been determined that a forest products industry in Alaska has a greater potential to be successful if marketed locally, the harsh seasonal conditions of Alaska could substantially affect WPC product durability, and thus its marketability.

PROJECT OBJECTIVES

The goal of this study is to develop and demonstrate that commercially viable wood plastic composite products can be produced using low-value waste streams from secondary industry and woody biomass from urban wood waste lots. It is also important to gain further understanding of how environmental exposure on such products affects mechanical properties, as well as the viscoelastic response. Thus, this project has two distinct objectives as outlined below:

1) Establish benchmark physical and mechanical properties of WPC boards made with Alaskan low-value woody material using ASTM standards and compare these results to those of WPCs made with more widely used feedstock within the WPC industry, namely white pine (*Pinus strobus*) fiber.

2) Assess the effects coupled environmental exposure (UV and freeze-thaw cycling) has on WPC strength, stiffness, and viscoelastic response.

THESIS OUTLINE

The following thesis will be outlined into four chapters. The first chapter will introduce the topics of the study, giving reasoning for the study itself and outlining the project objectives. The second chapter is a feasibility study on the use of Alaskan feedstock for WPCs where benchmark physical and mechanical properties will be established and compared to more widely used industry feedstock. The Third chapter will assess the effects coupled environmental exposure has on strength, stiffness, and viscoelastic response of WPCs. The fourth chapter will be the conclusion chapter of the thesis, where findings from chapters 2 and 3 will be presented and recommendations for further research will be discussed.

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CHAPTER TWO: URBAN WOODY BIOMASS AS FEEDSTOCK FOR WOOD-PLASTIC COMPOSITES

ABSTRACT

The goal of this study was to develop and demonstrate that commercially viable WPC products can be produced using low-value waste streams from secondary industry and woody biomass from urban wood waste lots. Experiments characterizing raw material and extruded composite physical performance were conducted; the results of which were compared to widely used pine feedstock under the same experiments. Particle size analysis of raw materials indicated a wider particle size distribution in birch and especially WBM samples relative to pine. Statistically lower diffusion coefficients associated with Alaskan material were also found during water soak testing. However, mechanical testing of specimens found no statistical difference in flexural strength, stiffness, creep recovery, or fastener withdrawal tests between any of the feedstock types. As a result, WPCs made with the two Alaskan low-value woody materials should be considered a viable option for the Alaskan forest products industry.

INTRODUCTION

Although the forest products industry in Alaska has been suffering over recent years, a general trend showing an increase interest in a secondary forest products sector may give opportunity for future investments to help rebuild a struggling industry (Braden et al 2000). Any such investment would be more profitable if low-value woody biomass, such as urban waste or harvested trees from treatments of urban-forest interface areas, could be utilized for production of high quality products. One such option for the use of low-value material is wood plastic composite (WPC) technology. WPCs use varying proportions of thermoplastic polymers and lignocellulosic material to produce a fiber/polymer matrix composite through extrusion or molding techniques. Commercial products often utilize reclaimed wood, used pallets, and sawdust for woody feedstock to reduce overhead costs and increase consumer perceptions (Trex 2009).

The use of various recycled material as feedstock for WPCs has been researched and found viable in multiple studies (Ashori et al. 2008; Kamdem et al. 2004; Stark 1999; Youngquist et al. 1995). Sources of recycled feedstock have been quite varied in studies, ranging from recycled newspapers (Ashori et al. 2008; Youngquist et al. 1995) to scrap pallets (Stark 1999), to CCA treated wood removed from service (Kamden et al. 2003). Regardless of the source, most studies have found composites comprised of these materials to produce acceptable physical/mechanical properties and possess distinctive characteristics. WPCs produced with wood fiber derived from scrap pallets and crates have shown greater strength and decreased percentages of shrinkage in laboratory testing when compared to commercially available pine wood flour (Stark 1999). Compression molded panels comprised of CCA-treated

lumber showed increases in strength and stiffness properties, as well as a greater resistance to photodegradation and fungal decay compared to non-treated lumber (Kamdem et al. 2004). Also, recycled newspapers used as composite reinforcing filler were found to provide better physical/mechanical properties than wood flour (Ashori et al. 2008; Youngquist et al. 1995).

Other studies have investigated the use of first generation low-value woody biomass material in WPCs. First generation refers to a material that was not used in a commercial product prior to its implementation as composite feedstock. A study by Englund (2008) investigated the use of low-value hybrid poplars as feedstock in WPCs and found physical and mechanical properties of such composites statistically similar to control specimens produced with 40-mesh maple flour. These results prove to be interesting because flexure testing of solid wood specimens of the same species performed in this study showed strength and stiffness values of the hybrid poplar clones to be significantly less than maple. Another study by Peterson (2008) found that WPCs produced with Alaskan beetle-killed Spruce, regardless of deterioration level, exhibited physical and mechanical properties just as good if not better than more widely used pine flour. Thus, it is reasonable to say that commercially viable WPC deck boards can be produced using feedstock with otherwise limited structural applications.

It is important, however, to consider the effects of environmental exposure upon the physical and mechanical properties of composites produced with never before used woody feedstock. Although performance may seem adequate in ambient testing conditions, the application of moisture, freeze-thaw cycling, or extreme temperatures may significantly alter properties of WPCs. Because of the hydrophilic nature of wood, moisture has been found to cause swelling in wood cell walls, resulting in a subsequent degradation of the mechanical bond between the wood and plastic and decrease in composite strength and stiffness (Stark 2001).

Freeze-thaw cycling has been shown to cause similar degradation of the fiber/polymer mechanical bond, also resulting in loss of structural properties (Panthapulakkal et al. 2006; Pilarski et al. 2006; Peterson 2008). Temperature has been found in multiple studies to influence the flexural strength and stiffness of WPC lumber (Lopez et al. 2005; Peterson 2008; Carrol et al. 2001), and should be considered when analyzing new composite products. Therefore, in order to properly evaluate the performance of WPCs, investigations on the effects of common environmental exposures experienced in product end use should be conducted.

Additionally, fastener capacity and creep response of WPCs should be investigated for new products. Although fastener capacities tend to be higher in wood-fiber/polymer composites as opposed to traditional wood products (Carroll et al. 2001; Falk et al. 2001), capacities vary between composite formulations and, like traditional wood products, is likely dependent upon specific gravity (Wilkinson et al. 1970). Creep response is an important characteristic considering the long durations of load experienced by WPC decking products. Because of the viscoelastic nature of both wood and plastic, composite products will show an increase in strain over time under sustained loading, possibly resulting in failure (creep rupture) at stress levels much lower than ultimate strengths achieved by short term laboratory testing (Lee et al 2004).

The main objective of this study is to establish benchmark physical and mechanical properties of wood plastic composites using low-value woody feedstock from Alaska and compare their results with current industry standard feedstock to produce WPCs. In order to accomplish this objective, the study is broken down into four tasks:

1) Characterize thermal properties and particle size distribution of feedstock from Alaska.

2) Produce deck boards made from Alaskan woody feedstock using common extrusion techniques and assess production output rates, densities, and machine thrust.

3) Establish benchmark physical and mechanical properties of extruded boards through standard testing protocols. Properties evaluated will include flexure under various environmental conditions, creep recovery, fastener withdrawal, and long term moisture soak tests.

4) Compare the results of tasks 1-3 to WPC specimens manufactured from commercially available pine wood flour to examine the commercial feasibility of using Alaskan low-value feedstock for WPC production.

MATERIALS AND METHODS

Material Preparation

This study investigated the feasibility of using two sources of low-value Alaskan woody material sources: native Alaskan Birch chips and residential woody-biomass material. The Alaskan birch (*Betula neoalaskana*) was collected locally in the Mat-Su region of Alaska and processed into chips at Poppert Milling in Wasilla, Alaska. The chips were fed through a hammermill to obtain a 60 mesh particle size wood flour. Wood flour was dried to a moisture content less than 2% using a conical steam tube dryer and stored until extrusion. Residential woody-biomass material (WBM) came from a residential landfill used by Anchorage homeowners to dispose residential trees, brush, and woody debris. Further information on the sources and species, used to procure the material is available in Appendix A. To prepare the WBM for processing into wood flour, further sorting was necessary to remove unwanted dirt, rocks, and other material unsuitable to be run through the hammermill. WBM was screened using a large rotating screening table fitted with a screen consisting of 19 x 19 mm holes. With the aid of manual filtering, sufficient amounts of unwanted material was removed and further processing into wood flour was achieved using the same methods as the birch previously described. Commercially acquired 60-mesh white pine flour (American Wood Fiber 6020BB) was dried and used as feedstock for control specimens.

Material Characteristics

Particle size and thermo gravimetric analysis (TGA) were performed on all three wood flour sources in order to characterize particle size distributions and thermal properties respectively. Particle size analyses were conducted using a Ro-Tap sieve analyzer with a series of stacked screens with decreasing screen sizes from top to bottom. A small sample of wood flour is placed on the top screen and sealed, where the instrument is then turned on and allowed to run for approximately 10 minutes. Weight retention by each sieve size was measured and recorded.

A small test specimen consisting of approximately 10 mg of moisture free wood material was placed into the TGA cell. Temperature was ramped isothermally in the nitrogen rich environment from 30°C to 550°C at 10°C/min. During temperature ramping, weight loss versus temperature was graphed. These graphical outputs give indication of the onset of initial and maximum degradation temperatures.

WPC Production

WPC deck boards used in this study were produced using an 86 mm counter-rotating conical twin screw extruder. In order to compare results with those of studies on WPC's with beetle-killed Spruce from Alaska, similar proportions of wood, plastic, and additives were used. In all, three formulations were used, difference being in the type of woody biomass used for wood flour production . Formulations consisting of 58% wood flour, 32% HDPE 2% zinc stearate, 1% EBS wax, 5% talc, and 2% zinc borate were dry blended for approximately 10

minutes and then vacuum fed to the extruder. The mixtures were melt-blended at a constant barrel temperature profile of 177°C and extruded into rectangular 135 X 25 mm cross sections at a 16 rpm screw speed. After cooling in a water spray chamber, they were cut into desired lengths. Records of machine torque amp, screw thrust, melt temperature, and output rate during extrusion were kept.

Testing Procedures

Flexure

Flexural properties of extruded WPC deck boards were evaluated following the guidelines outlined in ASTM D7032-08 testing standards. Test specimens were exposed to various environmental conditions as specified in the testing standards to determine baseline flexure properties and change in these properties due to temperature effects, moisture effects, and freeze-thaw cycling effects. All tests were performed in a testing lab with ambient conditions of 21°C and 50% relative humidity with a total of 10 replicates per conditioning type.

Baseline flexure values were conditioned in the testing lab with ambient conditions for a minimum of 48 hours before testing. For moisture effect, pecimens were submerged in tap water for a period of 4 weeks before testing. As for temperature effects, specimens were exposed to upper (52°C) and lower (-29°C) bound temperatures for a period of 24 hours before being tested in flexure. Freeze-thaw resistance specimens were exposed to three freeze-thaw cycles before being tested. One cycle consisted of a 24-h water soak in tap water, a 24-h freeze at 29°C, and a 24-h thaw in ambient conditions (21°C, 50% RH).

Prior to testing, measurements of width, thickness, and mass were recorded for each specimen in order to acquire accurate values of specimen stresses, strains, and densities. In accordance with ASTM D7032, setup and testing of flexure specimens were performed per ASTM D6109. This standard outlines a third point bending setup in which deck boards are supported at ends and have loads applied at the third points (Fig 2.1). The loading noses and supports were cylindrical surfaces with 12.7 mm radii. The test span was based off a 16:1 length to nominal thickness ratio, yielding a 406.4 mm span from the nominal specimen thickness of 25.4 mm. The testing apparatus used was a hydraulic driven crosshead with a 150 KN load cell. Mid-span deflections were taken using a +/- 25.4 mm linear variable differential transformer (LVDT). A constant crosshead speed of 12.03 mm/min was applied to specimens until failure while load and mid-span deflection measurements were recorded at a collection rate of 2 Hz. In order to gather information on material behavior, values of load-deflection were converted to stress-strain. Stress was calculated using the equation:

$$\sigma = \frac{PL}{bd^2} \qquad (1)$$

where σ = stress in the outer fibers of the composite, MPa; P = load applied to the center of the board, N; L = support span, mm; b = width of beam, mm; and d = depth of beam, mm.

Strain was calculated using the equation:

$$r = \frac{4.7\Delta d}{L^2} \qquad (2)$$

where r = flexural strain, mm/mm; Δ = mid-span deflection, mm; d= depth of beam, mm; and L = support span, mm.

Figure 2.1: Typical flexure setup per ASTM D7032 specifications

Modulus of elasticity (MOE) was calculated by determining the slope of the stress-strain graph between the 10% and 40% of maximum stress values (the elastic range of the graphs) as specified by ASTM D7032. Values of modulus of rupture (MOR) were found by calculating maximum flexural stress at point of specimen failure.

Creep Recovery

As per ASTM D 7032, 24-h creep recovery tests were performed on five specimens per feedstock type (15 total) to gain an understanding of the short term viscoelastic response of the formulations. Creep recovery is a third point bending test in which specimens are subjected to a constant load for a 24 hour duration and then allowed to recover for another 24 hours with no superimposed loads. Testing standards specify that mid-span deflection measurements are to be made: (1) prior to load application, (2) immediately after load application, (3) at 24 hours with

the load on, and (4) after the 24-h recovery period. From this data, total mid-span deflection of the 24-h loading period was calculated using the equation:

$$\Delta_{total} = \Delta_{24} - \Delta_0 \quad (3)$$

where Δ_{total} = Total deflection experienced during the 24-h loading period, mm; Δ_{24} = deflection at the end of the 24-h loading period, mm; and Δ_0 = deflection immediately after application of load, mm. Percent recovery was calculated using the equation:

$$\%_{recovery} = (\Delta_{recovered}/\Delta_{total})*100\% \quad (4)$$

where $\%_{recovery}$ = Percentage of deflection recovered in 24-hrs after 24-h loading period; $\Delta_{recovered}$ = recovered deflection in 24-hrs after 24-h loading period is complete, mm; and Δ_{total} = total deflection experienced during the 24-h loading period, mm.

The test setup was similar to that of the flexure tests in that a test span of 406 mm was used and loads were applied at the third points of the boards. ASTM D7032 specifies to load specimens in flexure to twice the design load for which code recognition is desired. The 2005 IBC specifies a load rating of 4.788 kPa for residential decking, so twice the design load would yield 9.576 kPa. Values of bending moment and stress were calculated considering the actual dimensions of test specimens and a uniform load across the length of the beam. In order to apply the desired stresses upon specimens, applied loads were back-calculated using a third point flexure beam loading scenario. Desired loads were applied using an 8:1 pulley system and mid-span deflections were recorded using a calibrated dial gage mounted to an aluminum yoke (Fig 2.2). All specimens were allowed to equilibrate to the testing conditions (21°C, 50% RH) for a minimum of two days.

Figure 2.2: Example of creep recovery test setup (note: actual test specimens not shown)

Screw Withdrawal

Screw withdrawal tests were performed on five specimens per feedstock type in order to determine fastener capacities in decking applications. Tests were performed per ASTM D1037 specifications on full width and thickness specimens cut into 127 mm samples. Prior to testing, pilot holes were predrilled at the center of the wider surface, perpendicular to the plane of the boards a distance slightly past 16.9 mm using a 2.4 mm diameter drill bit (approximately 90% of screw root diameter). All purpose screws (#8 Hillman) that were 44.45 mm long, 2.79 mm in root diameter, and with yellow dichromate finish, were screwed into the pilot holes a depth of 16.9 mm perpendicular to the plane surface using a jig to ensure consistent screw penetration depths for all specimens. Screws were drilled just before testing in order to eliminate effects of material relaxation as much as possible.

A 2 kip electromechanical loading apparatus was used to test the specimens (Fig 2.3). A fixed mount was used to hold the deck board in a static position while a cable mounted to the

load frame and screw were displaced upward at a constant rate of 1.55 mm/min until fastener failure occurred. Maximum withdrawal load and individual specimen density were recorded for analysis.

Figure 2.3: Screw withdrawal test setup per ASTM D1037 specifications

Water Sorption and Thickness Swell

Long term moisture soaks of specimens were conducted to evaluate the effect moisture has on specimen water absorption and thickness swell. Five specimens per feedstock type were cut to 102 X 102 mm specimens and planed down to 6.35 mm thickness to eliminate surface effects of extruded boards. Removing the polymer rich surfaces expedites moisture infiltration into the specimen, allowing for a more severe evaluation of moisture effects. Specimens were submerged in a tap water bath for a total of 18 weeks. Measurements of mass and average

thickness were taken in order to evaluate moisture uptake over time. Thickness was the average of five thickness measurements on each specimen using a dial gage. The positioning of the five measurements was consistent from specimen to specimen, which was ensured using a pre-fabricated template. Daily measurements of mass and thickness were taken for the first three days. Thereafter, weekly measurements were taken for the first six weeks, after which measurements were taken at 8, 10, 12, 14, and 18-week periods. Percent mass gained and percent thickness change were calculated using initial measurements of specimens before submersion into water. Moisture diffusion coefficients were also calculated to determine the rate of moisture penetration through the composites. Coefficients were calculated for all samples using the following equation (Shen et al. 1976):

$$D_A = \pi \left[\frac{mh}{4M_{sat}} \right]^2 \left[1 + \left(\frac{h}{L} \right) + \left(\frac{h}{n} \right) \right]^2 \qquad (5)$$

Where: D_A = water diffusion coefficient corrected for edge effects, mm^2/h; m = linear portion of water absorption against square root of time; M_{sat} = assumed saturation point after 18 weeks; h = thickness, mm; and L = length, mm.

RESULTS AND DISCUSSION

Material Characteristics

Particle size distribution

The mechanical performance of extruded wood plastic composites is highly dependent on the mechanical bond between the wood particles and thermoplastic resin. A study by Stark and Rowlands (2003) showed the length to depth ratio of wood fibers, often referred to as aspect ratio, has a large influence on WPC strength and stiffness properties. Although there was not a direct correlation between particle size and aspect ratio, smaller particle sizes seemed to exhibit higher aspect ratios than larger particles. Particles retained on a 70 mesh screen size attributed the highest aspect ratio for the ponderosa pine wood flour, while particles retained on the 35 mesh screen size were the lowest. Tensile strength was shown to be highest in extruded composites containing the 70 mesh wood flour while lowest in composites containing the 35 mesh wood flour. Tensile modulus was shown to be lowest in composites containing the 35 mesh flour, but no statistical difference in tensile modulus was found due to differences in particle sizes. Therefore, it is important to assess the particle size distribution of wood flour before extrusion so that the proper hammermill screen size can be used if milling is required, and so a general idea of relative composite performance can be developed before production. Studies have also found that particle size has a direct influence upon composite density, with smaller particles producing higher density products (Chen et al. 2005)

To establish an acceptable screen size for milling Alaskan WBM, three iterations of small samples were milled using different screen sizes. The corresponding particle size distribution for

each screen size was compared to commercially acquired white pine wood flour (Table 2.1 and Fig 2.4). The screen size containing a distribution closest to the pine was used throughout the processing stage. In the study by Peterson (2008), 1.17 mm screen size mesh was used to mill the beetle-killed spruce. This size, along with 0.79 mm and 0.69 mm meshes were used to produce small samples of milled WBM flour.

A particle size distribution was first performed on the commercially acquired White Pine wood flour to establish baseline distribution. It was found that 90-95% of all pine flour was retained by the 60 and 80 Tyler mesh screens, with trace amounts retained in higher and lower screen sizes. The 1.17 mm mesh created a particle size distribution that had a high percentage (about 60%) of retained WBM flour clustered around the 60 and 80 Tyler mesh screens, but did have considerably higher percentages of flour retained in the upper and lower mesh sizes. The 0.79 mm mesh contained a slightly higher percentage of retained flour retained around the 60 and 80 meshes (about 70%), which generated a smaller, but still present, retention in the upper and lower screen sizes. The 0.69 mm mesh retained a high amount of flour on the 60 and 80 screens (about 75%) and had relatively low retention on the upper and lower screens. It was decided, however, that the 0.79 mm screen would be used for the rest of the milling.

In order to remain consistent, the 0.79 mm mill screen size was also used to process the birch into wood flour. It was found that a very high percentage of particles (about 85%) were retained on the 60 and 80 Tyler mesh screens. Comparison of birch wood flour with WBM milled with 0.079 mm screen and the 60 mesh pine (Table 2.2 and Fig 2.5) found that pine contains the “tightest” particle size distribution with almost no presence of fines (100 Tyler mesh size or greater) or large particles (40 Tyler mesh size or less). This is expected as other particle sizes are filtered out by the flour manufacturer. The WBM contained the “widest” particle size

distribution, with a significant presence of fine and large particles. Milled Birch flour contained a large amount or particles in the 60 to 80 Tyler mesh size range; there was a presence of large and fine particles, but not as much as the WBM. A larger presence of finer particles in milled WBM flour may be a result of the increased amount of non-woody material in the WBM, such as bark, pine needles, dirt, and etc.

Table 2.1: Particle size analysis of WBM using different mill screen sizes and 60 mesh pine

Tyler Mesh Size	% Retained			
	60 Mesh Pine	WBM @ 1.17 mm	WBM @ 0.079 mm	WBM @ 0.069 mm
20	0.0	1.1	1.4	0.2
40	0.1	16.8	9.6	7.9
60	17.0	36.9	30.1	27.0
80	78.3	23.6	40.5	50.2
100	0.6	10.1	8.2	5.3
120	1.7	7.6	1.6	5.3
pan	2.4	3.9	8.7	4.1

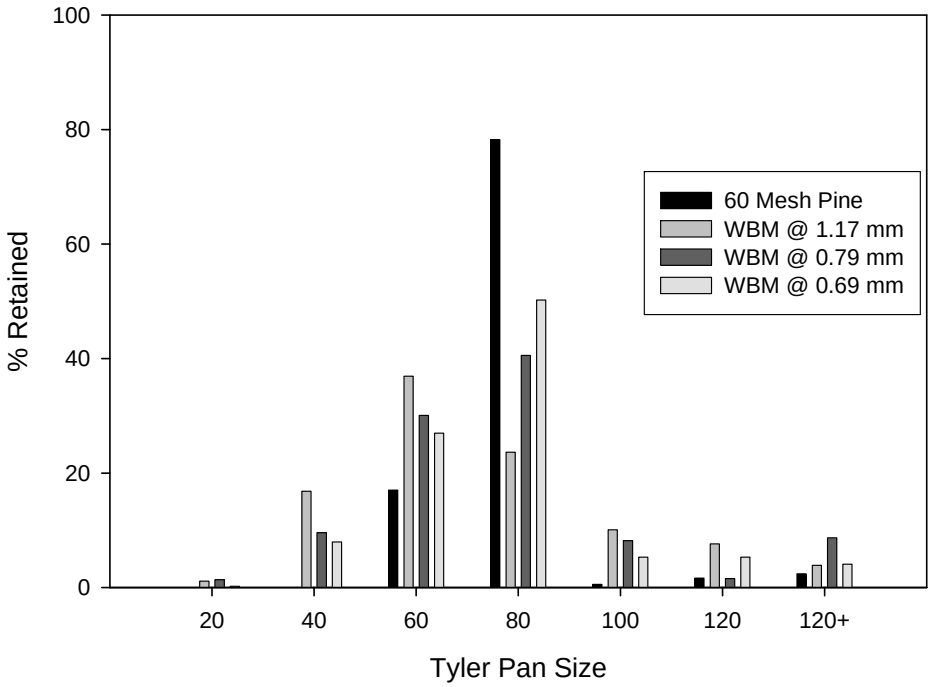

Figure 2.4: Particle size analysis of WBM @ different mill screen sizes compared to 60 mesh pine

Table 2.2: Particle size analysis of all feedstock types

Tyler Mesh Size	% Retained		
	60 Mesh Pine	WBM @ 0.79	Birch @ 0.79 mm
20	0.0	1.4	0.0
40	0.1	9.6	6.7
60	17.0	30.1	60.2
80	78.3	40.5	27.6
100	0.6	8.2	2.3
120	1.7	1.6	1.6
pan	2.4	8.7	1.6

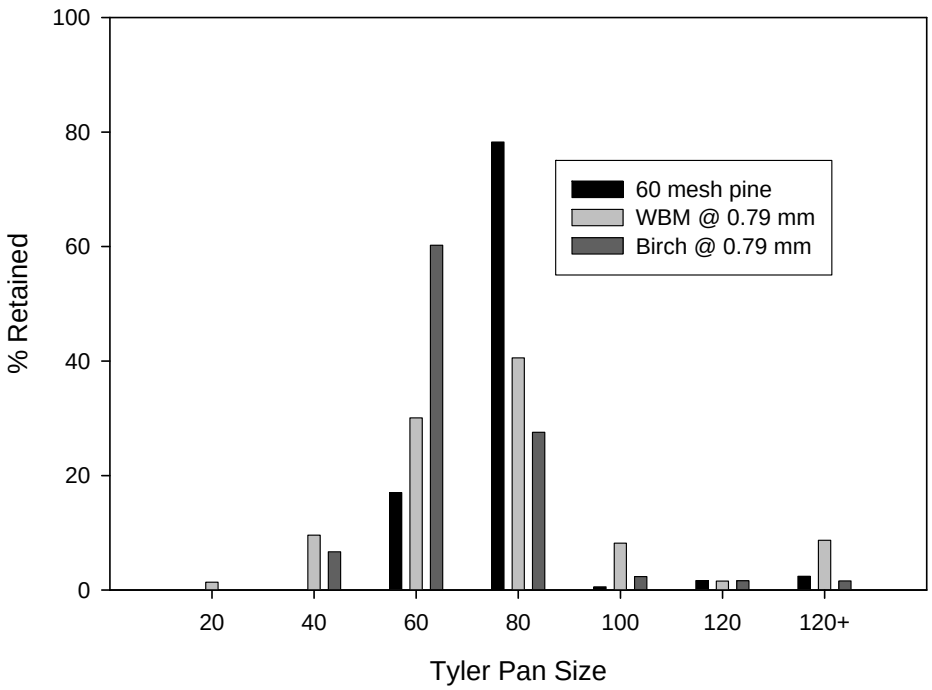

Figure 2.5: Particle size analysis of all feedstocks

Thermagravimetric Analysis

TGA testing was performed to characterize initial and maximum degradation temperatures of pine, birch, and WBM wood flour feedstocks. Pine displayed the lowest initial degradation temperature at 225°C, as well as the highest maximum degradation temperature at 323°C. Birch specimens had an initial degradation temperature of 236°C and maximum degradation temperature of 314°C, while WBM specimens had a 234°C and 312°C initial and maximum degradation temperatures respectively. Although slight differences in the thermal properties of each feedstock are present, no feedstock appears to be in danger of degradation during extrusion considering the much lower barrel temperatures used for melt blending (177°C).

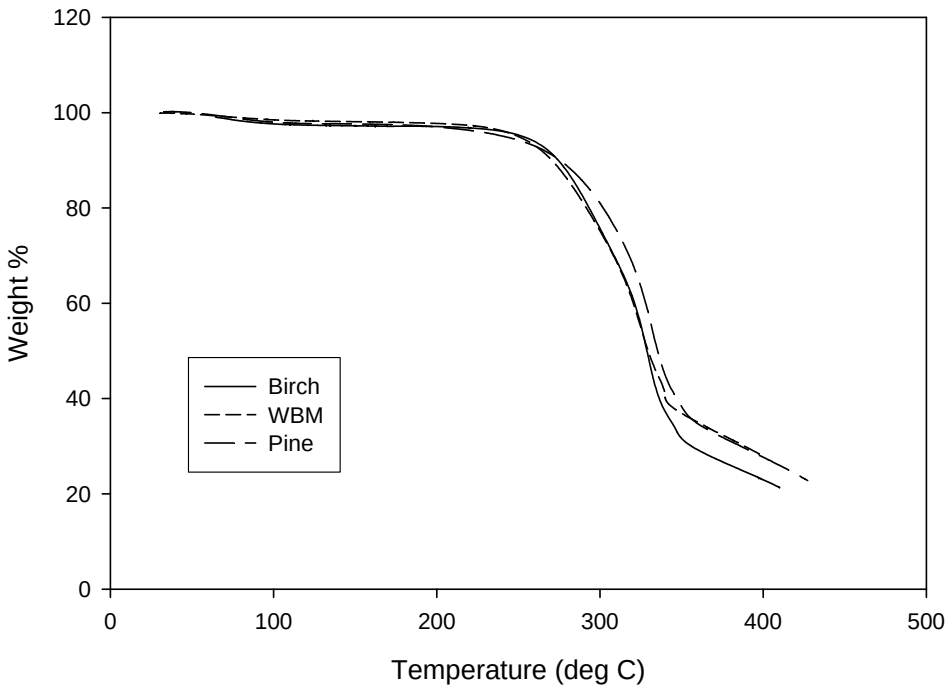

Figure 2.6: TGA of birch, WBM, and pine wood flour

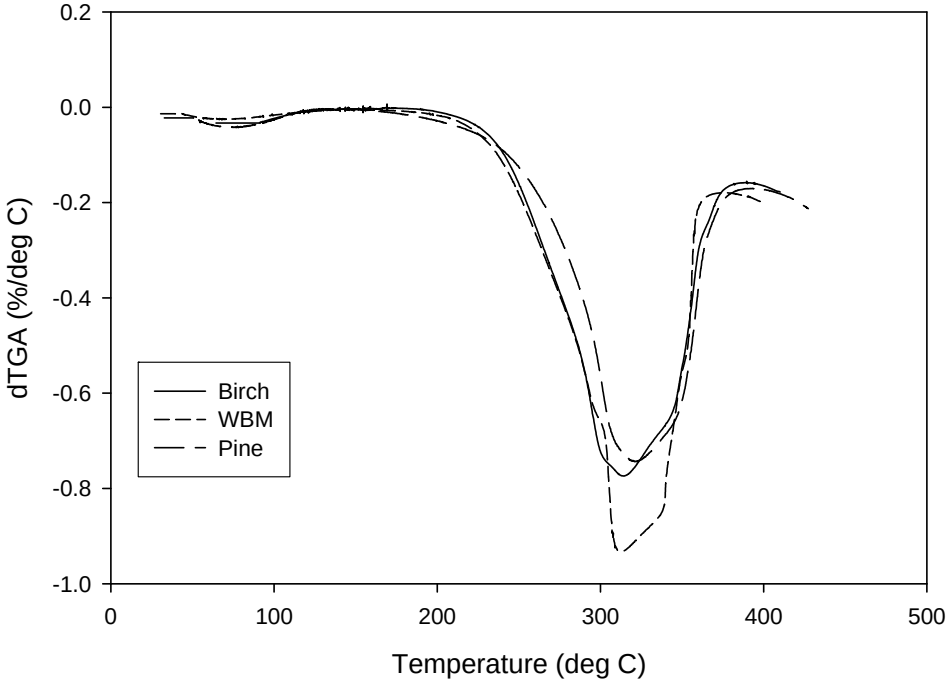

Figure 2.7: dTGA of birch, WBM, and pine wood flour

Production Characteristics

Records of machine torque amp, screw thrust, melt temperature, and output rate were kept during deck board extrusion. Machine torque amp, screw thrust, and melt temperature remained relatively constant regardless of feedstock type at 35%, 20%, and 177°C respectively. Output rate and board densities, however, did slightly vary from formula to formula. Boards produced with pine feedstock had an extrusion output rate of 216.2 kg/hr, whereas WBM and birch boards had rates of 247.5 and 264.0 kg/hr respectively. Pine boards had an average density of 1179 kg/m^3, with WBM and Birch boards having average densities of 1186 and 1161 kg/m^3 respectively.

Output rate of boards produced with WBM and birch feedstock were slightly higher than pine. Smaller sized wood particles in composites can lead to slightly higher shear viscosities

during extrusion (Hristov et al. 2008; Li et al. 2005), resulting in greater compounding and extrusion rates of composites. Therefore, the smaller particles present in birch and WBM milled fibers may explain the increase in production rates. Board densities were very similar between feedstock types, with WBM possessing slightly higher values that pine and birch boards. Studies have found composite density to increase with smaller wood fiber particle sizes (Chen et al. 2005), explaining why WBM boards, with a higher percentage of smaller particle size, possess a slightly higher density. Although, this hypothesis may not be sufficient, considering the birch feedstock specimens did not have a higher density than pine boards. Surface quality of extruded boards looked very good for pine and WBM feedstock, but birch boards had several large sections containing surface defects. The origin of these surface defects was unknown, but could have resulted because of poor ventilation of volatile gases in the melt and mixing chambers of the extruder.

Mechanical Characteristics

Flexure Stiffness

Results of stiffness values from specimen flexure testing are presented in Table 2.3 and Figure 2.8. Testing in ambient conditions found WBM specimens to possess the highest values of MOE, followed by pine and birch. Stiffness values of birch were statistically lower than pine and WBM, but no significant difference was found between WBM and pine specimens. Generally, pre-treatment with temperature, moisture, and freeze-thaw cycling caused significant changes in MOE values for each feedstock type compared to non-treated specimens. Moisture, freeze-thaw cycling, and high temperature conditioning of specimens all caused average

decreases, while cold temperature exposure resulted in an increase in stiffness for all feedstock types.

In general, exposure had the greatest change in stiffness values for pine than any other feedstock source, but WBM specimens reacted statistically similarly to pine in most exposure types (except hot temperature and moisture exposure). Birch specimens acted quite differently than pine and WBM, exhibiting statistically higher resistance to exposures where MOE was generally decreased (moisture, high temp, and freeze-thaw) and lower resistance where MOE was generally increased (cold temp). Birch specimens showed the highest influence when exposed to cold temperature testing, but pine and WBM were influenced the greatest by high temperature testing. It should be noted, however, that in every exposure type except for cold temperature, WBM and birch specimens produced average stiffness values higher (although not statistically significant) than Pine.

Table 2.3: Stiffness properties of WPC produced from Alaskan woody material and Pine

Feedstock	Ambient (GPa)	Moisture (GPa)	Change (%)	Cold Temp (GPa)	Change (%)	High Temp (GPa)	Change (%)	F-T Cycling (GPa)	Change (%)
Pine	4.02 (1.8%)	2.70 (2.4%)	-32.7**	5.17 (1.6%)	+28.7**	2.08 (1.5%)	-48.2**	2.88 (2.9%)	-28.4**
Birch	3.55 (1.9%)	3.11 (9.1%)	-12.6**	5.15 (3.4%)	+45.0**	2.44 (2.4%)	-31.5**	3.12 (1.3%)	-12.2**
WBM	4.12 (1.1%)	2.84 (1.0%)	-31.0**	5.11 (0.7%)	+24.0**	2.31 (1.7%)	-44.0**	3.13 (1.2%)	-24.0**

Percent CV shown in ()
** significant at 95% level

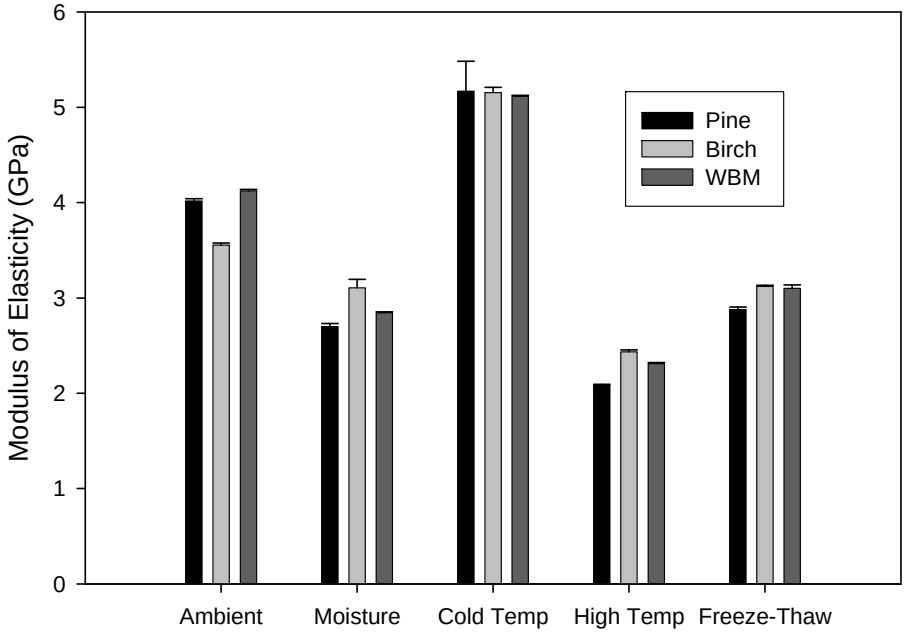

Figure 2.8: Modulus of Elasticity (GPa) of WPC boards tested in flexure with various exposures

Flexure Strength

Results of strength values from specimen flexure testing are presented in Table 2.4 and Figure 2.9. Like stiffness results, testing in ambient conditions found WBM specimens to possess the highest values of MOR, followed by birch and pine. Strength values of WBM boards were statistically higher than pine, but no difference was found between WBM and birch. Moisture and freeze-thaw cycling had no statistical effect upon the values of MOR for any feedstock compared to ambient testing conditions. It was also found that the effects of moisture and freeze-thaw cycling had very little effect on strength values when compared to the statistically more drastic effects of hot and cold temperature exposure.

Like stiffness values, pine feedstock boards generally exhibited the largest changes in strength values due to exposure, although only statistically significant in the case of high

temperature exposure. In cold temperature flexure testing, pine specimens produced an average of 51% increase of strength values while birch and WBM saw 42% and 45% increases respectively. In high temperature testing, pine again saw the most dramatic influences on strength values, with a 36% average loss, while birch and WBM specimens experienced a loss of 27% and 28% in strength, respectively.

Table 2.4: Strength properties of WPC produced from Alaskan woody material and Pine

Feedstock	Ambient (MPa)	Moisture (MPa)	Change (%)	Cold Temp (MPa)	Change (%)	High Temp (MPa)	Change (%)	F-T Cycling (MPa)	Change (%)
Pine	21.5 (6.9%)	20.7 (5.9%)	-3.9	32.4 (2.7%)	+50.5**	13.8 (1.9%)	-35.8**	21.4 (6.0%)	-0.56
Birch	22.2 (1.7%)	22.3 (6.7%)	+0.3	31.4 (4.0%)	+41.5**	16.1 (1.6%)	-27.4**	21.6 (1.6%)	-2.63
WBM	22.9 (1.3%)	22.4 (2.0%)	-2.4	33.2 (1.6%)	+44.9**	16.5 (1.5%)	-28.2**	22.7 (1.3%)	-1.03

Percent CV shown in ()
** significant at 95% level

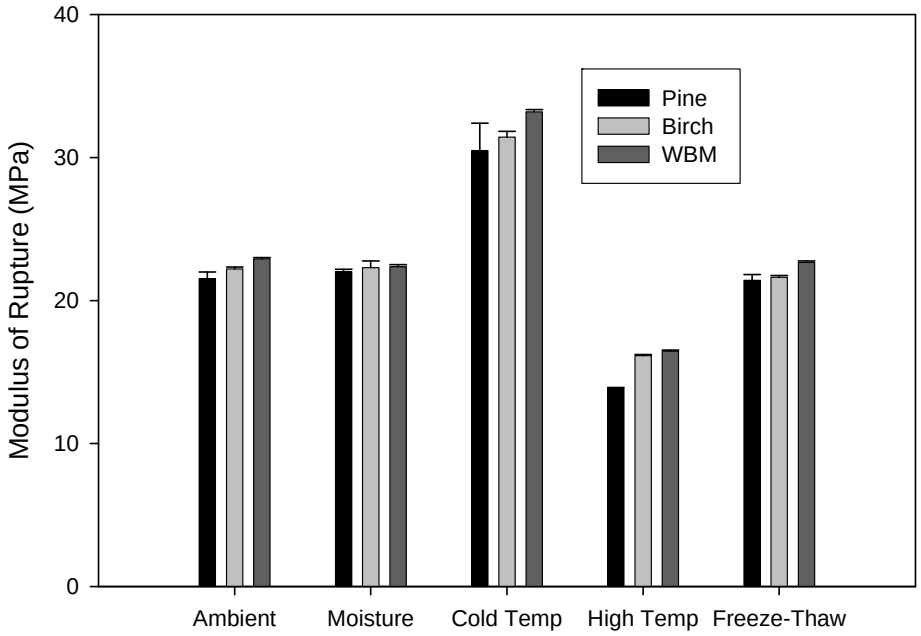

Figure 2.9: Modulus of Rupture (MPa) of WPC boards tested in flexure with various exposures

Creep Recovery

Results from flexural creep recovery tests are presented below in Table 2.5. Overall, pine exhibited the largest average total deflection and the lowest recovery percentages at the instantaneous and 24h time periods. Birch and WBM produced similar results, with WBM specimens performing slightly better with a lower total deflection and higher percentage of recovery at both time periods. The differences in total deflection of pine with respect to birch and WBM specimens were initially found to be statistically significant, but further analysis using specimen density as a covariant revealed the differences to be insignificant. Differences between feedstock types regarding instantaneous and 24h creep recover were found to be insignificant as well.

Table 2.5: Creep recovery performance of boards tested in flexure

Feedstock	Total Deflection	Instant. Recovery (%)	24 H Recovery (%)
Pine	1.01 (4.9%)	56.1 (5.1%)	81.9 (7.5%)
Birch	0.83 (3.5%)	57.1 (6.5%)	84.8 (5.2%)
WBM	0.81 (9.1%)	57.7 (6.7%)	86.5 (5.0%)

Percent CV shown in ()

Screw Withdrawal

Results from screw withdrawal tests are reported as the maximum withdrawal load during testing. Failure in the testing scenario occurred only from screw withdrawal. Although never encountered in testing, any failure occurring due to screw breaking would have been noted and discarded from test data per ASTM D1037. Presented below in Table 2.6, pine exhibited the highest average withdrawal strength, closely followed by birch specimens. WBM produced the lowest average withdrawal strength, and also had the highest average board density of any

feedstock source. However, despite slight differences, results of failure loads were not statistically significant between feedstock types.

Table 2.6: Average screw withdrawal strength of WPC specimens

Feedstock	Avg. Max Load (kN)	Board Density (kg/m^3)
Pine	1.52 (6.8%)	1174 (0.4%)
Birch	1.51 (2.8%)	1167 (1.4%)
WBM	1.43 (5.6%)	1182 (0.2%)

Percent CV shown in ()

Water Sorption and Thickness Swell

Graphical results of water sorption and thickness swell tests are presented in Figures 2.10 and 2.11. Initial weeks of testing indicate that specimens produced with pine feedstock had higher levels of water sorption and thickness swell than birch and WBM specimens. However, especially in the case of water sorption, the rate of moisture uptake in pine specimens appeared to taper off quicker relative to birch and WBM as time progressed, ultimately resulting in a lower final percentage of mass change. Pine had the lowest overall average percentage of mass change in specimen testing with a 20.9% increase, while birch and WBM specimens had an average of 22.8% and 22.5% mass change respectively. Thickness swell results indicate that pine had the largest overall average percentage increase in specimen thickness with a 12% increase, while birch and WBM specimens had an average of 10.7% and 11.7% increase respectively.

Statistical analysis of diffusion coefficients found pine to have significantly higher diffusion rates, with average coefficients of 0.00839, 0.00532, and 0.00433 mm^2/h for pine, birch and WBM respectively. Other studies have found differences in water absorption rates between composite fiber types and were thought to occur because of differences in chemical composition, hydrophilic nature, or fiber shape (Tajvidi et al. 2005). No information is available on the

chemical composition or hydrophilic nature of the feedstocks used in this study, but fiber shape certainly differs as shown in the particle size analysis. The lower rates in birch and WBM specimens could be a result of a higher presence of fines or the collapse of fiber cell walls during processing, both of which would hinder the pathway of moisture flow.

Overall, all three feedstock types performed relatively similar to each other in water submersion testing. Although diffusion rates are significantly higher in pine specimens, final percentages of mass and thickness increase exemplify their similarities in moisture durability.

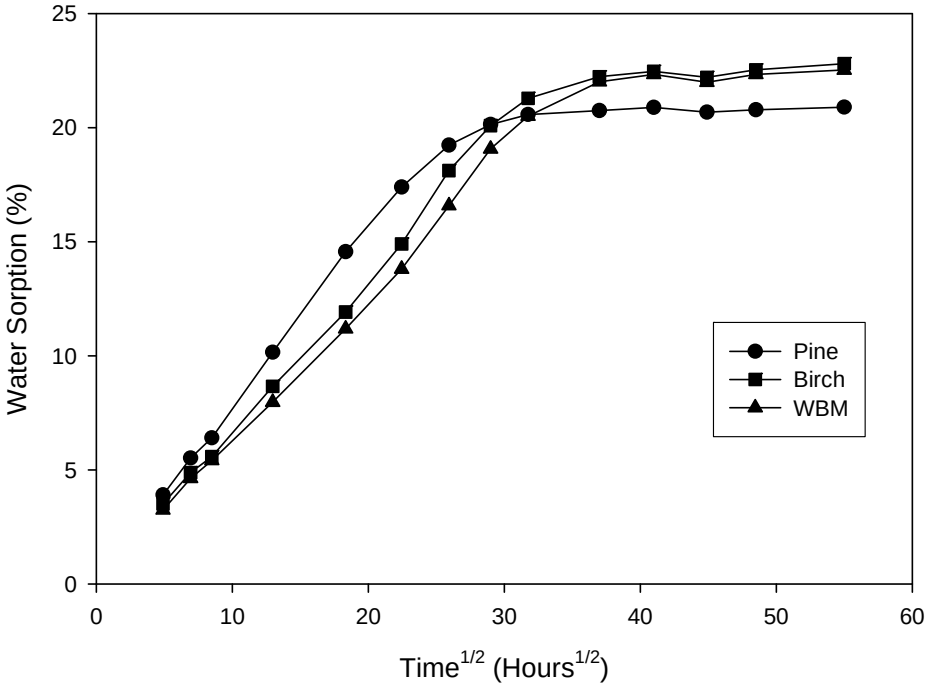

Figure 2.10: Percent mass change over time of specimens submerged in water for 18 weeks

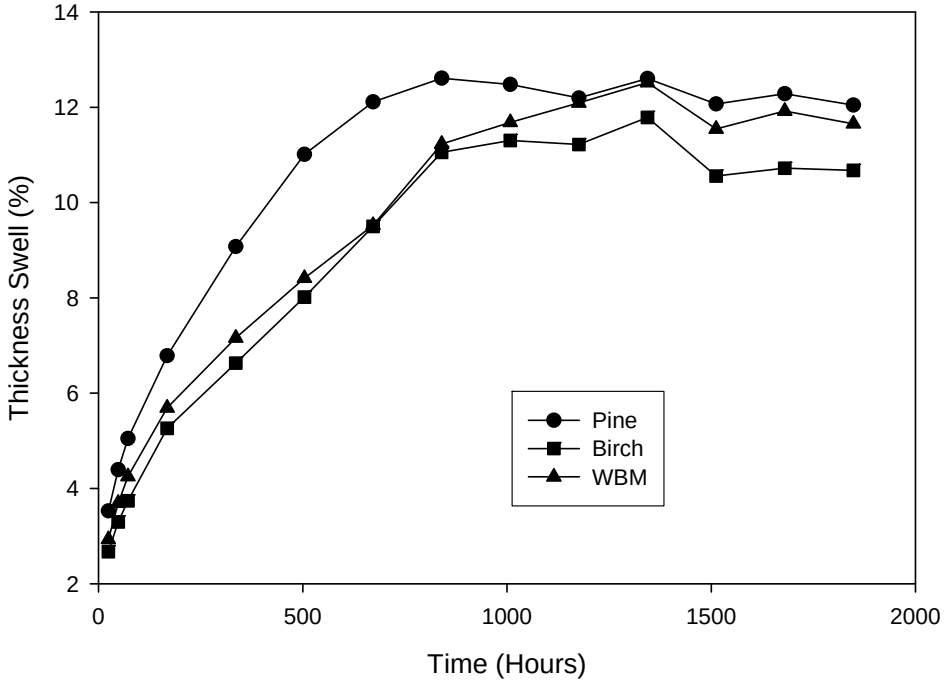

Figure 2.11: Percent thickness change over time of specimens submerged in water for 18 weeks

CONCULSIONS

The objective of this study was to assess the viability of using low-value Alaskan woody material as feedstock in extruded wood-plastic composite deck boards. In order to accomplish this, experiments characterizing raw material and extruded composite physical performance were conducted; the results of which were compared to widely used pine feedstock under the same experiments. Flexural results indicate that WBM and birch feedstock composites exhibit similar values of MOE and MOR as pine under various testing conditions. Creep recovery and fastener withdrawal testing also produced similar results between feedstock types. Pine specimens exhibited larger total creep deflections during creep recovery tests, but results were found to be directly related to specimen board density and not necessarily feedstock type. Results from fastener withdrawal tests indicate no statistical difference between feedstock types, although pine and birch specimens possessed slightly higher maximum loads than WBM. Particle size analysis of processed material showed a higher presence of fine particles in WBM and birch. Statistically lower diffusion coefficients associated with Alaskan material were also found during water soak testing.

Overall, WPCs made with the two investigated Alaskan low-value woody material exhibit similar physical and mechanical properties as commonly used pine wood flour, and thus should be considered as a viable option for the Alaskan forest products industry. However, further investigation should be done to evaluate creep parameters of such composites exposed to various weathering so that an idea of product performance in the harsh environmental conditions of Alaska can be developed.

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CHAPTER THREE: COUPLED WEATHERING EFFECTS ON STRENGTH, STIFFNESS, AND CREEP BEHAVIOR OF WOOD-PLASTIC COMPOSITES

ABSTRACT

Environmental exposure influences on mechanical properties, as well as viscoelastic response, of extruded wood-plastic composites (WPC) was investigated. Specimens were planed down and exposed to a combination of ASTM conditioning protocols consisting of ultra violet light exposure and freeze-thaw cycling. Once conditioned, specimens were subjected to static flexure and long term (90 day) creep testing to determine the influence of coupled weathering on mechanical performance. Static flexure results indicated a significant influence of weathering of specimens upon values of strength, stiffness, and strain to failure. It also appeared the coupled weathering created larger influences upon flexural properties than independent weathering. However, results suggest that freeze-thaw cycling had a significantly larger affect than UV exposure. Weathering of WPC caused significant increases in flexural creep strain as well, especially within the first minute of sustained loading. This is believed to occur as a result of the large influence weathering has upon static response of composites. Consequently, increases in creep strain after one minute and creep strain rates from weathering were not found to be statistically significant. Although not statistically significant, coupled weathering of specimens appeared to have a larger influence upon creep strains than independent weathering with freeze-thaw cycling and UV exposure.

INTRODUCTION

As a growing alternative to traditional treated lumber in outdoor applications, extruded wood plastic composites (WPCs) are often marketed as highly durable and requiring little to no maintenance during their intended end use. Consumer perception of WPCs seems consistent with these claims considering the stark increase in sales of residential WPC decking. As an estimated $700 million industry, it is forecasted that WPC decking will exhibit double digit growth in the foreseeable future (Lerner 2003).

However, despite their popularity and ever increasing market share in the forest products industry, research has shown that considerable surface quality deterioration does occur when WPC products are weathered in accelerated laboratory and *in situ* conditions (Kiguchi et al 2006). When WPCs were first introduced into the market, they were thought to be impervious to the effects of moisture. It was theorized that the hydrophobic, polymer rich surfaces of such products completely encapsulated the hydrophilic wood fibers and were thus protected (Morrell et al 2006). Long since disproved, it has been found that moisture is able to infiltrate into wood fibers in composite materials, causing swelling of wood cell walls and consequently decreasing the modulus of the wood fibers and the composite as a whole (Stark 2001). Swelling of wood cell walls has also been found to degrade the mechanical bond between the wood and plastic, causing a decrease in composite strength (Stark 2001). Repeated swelling and shrinking over time could eventually lead to micro-cracks in the composite which serve as ideal pathways for decay fungi and mold.

Because the effects of moisture have been found to be detrimental to the mechanical properties of WPCs, it would be safe to assume that freeze thaw cycling would produce similar,

if not more severe influences. Freeze-thaw cycling typically involves a period of moisture soak, followed by freezing then thawing. Studies have shown significant decreases in strength and stiffness values of WPCs exposed to accelerated freeze-thaw cycling in laboratory testing. Losses in properties were attributed to decreased bonding between wood fibers and plastic matrix, which were confirmed by scanning electron microscope (SEM) images (Pilarski et al 2006). Degradation of composite mechanical properties has also been found in natural fiber/polymer composites comprised of lignocellulosic material exposed to moisture and freeze-thaw cycling (Panthapulakkal et al 2006). Tests confirmed the notion that the hydrophilic nature of natural fiber fillers significantly affects composite strength and stiffness properties when exposed to moisture. It was also found that most of the degradation associated with freeze-thaw cycling was due to water penetration into the composites.

Another important aspect to consider when discussing the durability of WPC products exposed to environmental conditions is the affect of ultraviolet (UV) and infrared (IR) radiation from the sun. Studies have shown that wood fibers exposed to irradiation exhibit degradation of lignin and rapid changes in color (Pandey et al 2008; Pandey 2005). Polymers exposed to irradiation undergo chain scissions (White et al 2004; Stark 2006), thus shortening polymer chains and allowing for greater crystallinity because of their higher mobility (Jabarin et al 1994). When applied to WPCs, weathering results in lightening of surface color and loss of wood fiber content (Fabiyi et al 2008). Laboratory testing also shows loss in mechanical properties of composites exposed to irradiation (Lopez et al 2005; Stark 2006), but effects are generally much less than composites exposed to moisture and extreme temperatures (Lopez et al 2005). However, testing has found that WPCs exposed to a combination of irradiation and moisture is far more detrimental to physical and mechanical properties than irradiation alone (Stark 2006).

In their end use, WPC products are subjected to multiple environmental conditions simultaneously (i.e. sunlight, moisture, extreme temperatures), therefore laboratory testing of specimens exposed to coupled weathering may produce more realistic results in property losses than weathering using one condition exclusively and should be investigated further.

When speaking about the durability of WPCs, an important characteristic to consider is their time dependent behavior. Because of the viscoelastic nature of both wood and plastic, composite products will show an increase in strain over time under sustained loading, possibly resulting in failure (creep rupture) at stress levels much lower than ultimate strengths achieved by short term laboratory testing (Lee et al 2004). In an attempt to predict the linear and non-linear time dependent responses of WPCs, multiple studies have been conducted using various modeling techniques (Brandt et al 2003; Kobbe 2005; Rangaraj et al 1999; Lee et al 2004; Najafi A. et al 2008; Sain et al 2000). A widely accepted and effective model used is the power law introduced by Fidley in 1960 (Kobbe, 2005). Based upon a semi-empirical formula, the power law has been found in multiple studies to accurately predict the viscoelastic nature of WPC's during the primary and secondary stages of creep at low to moderate levels of stress (Kobbe 2005; Najafi A. et al 2008; Sain et al 2000). The power law can be used to estimate strain and strain rates of WPC's at particular time intervals, which could be useful to predict product performance in end use applications.

Past studies have found that the creep response of WPCs is very dependent on wood fiber loadings (Park et al 1998; Lee et al 2004) and environmental conditions such as temperature and moisture (Pooler et al 2004; Sain et al 2000; Najafi S. et al 2008). Generally, an increase in WPC fiber loading results in a reduction of creep strain due to an increase in specimen stiffness (Lee et al 2004; Park et al 1998). This influence can be viewed as a benefit

considering the economically priced and often recycled sources of wood fiber fillers. In terms of modeling, the effects of fiber loading and temperature can be accounted for using modeling constants and the time-temperature superposition principle. However, little is understood about the influences other environmental exposures such as moisture, irradiation, and freeze-thaw cycling will have on the long term response of WPC products or their implications towards accurately modeling.

A study conducted by Najafi S. et al (2008) investigated the effects of water absorption on the creep behavior of wood-HDPE composites. It was found that longer conditioning times of specimens in tap water baths resulted in an increase of initial and total creep strain in flexural creep testing. Results were thought to be consequence of the absorbed moisture causing fiber/matrix debonding, creating relaxation of molecules and larger deformations in testing. As discussed earlier, this degradation of fiber/matrix bond has also been observed in WPC specimens conditioned with irradiation and freeze-thaw cycling, but to date, no study has investigated their effects on the long term response of composite materials. Also, an investigation as to the effects of coupled weathering (i.e. combination of UV light and freeze-thaw cycling) on the creep response of WPCs would provide further insight into the long term durability of such products, considering their typical end use (decking, siding, etc.).

The goal of this study is to quantify and evaluate the effects of coupled weathering on the static and creep flexural behaviors of wood-fiber reinforced thermoplastic composites. In order to accomplish this objective, the study is broken down into the following tasks:

1) Pre-condition WPC specimens with UV and freeze-thaw using standardized weathering techniques

2) Perform static flexure testing to assess influence of weathering on strength, stiffness, and strain to failure
3) Subject specimens to creep loading and investigate creep strains at specific times to determine influence of weathering
4) Model creep response of WPC's using Findley's Power Law and use to calculate and evaluate creep strain rate at specific times
5) In conjunction with the study by Cameron (2009), comparison of weathering effects will be made between the feedstock types in order to determine the existence of any species effect.

Standardized weathering techniques will be used to appropriately condition specimens before testing so that results can easily be reproduced. Laboratory static flexure testing will be used to establish the effects of weathering on WPC strength, stiffness, and strain to failure, while also providing guidelines for appropriate stress levels to be used in creep testing. The effects of weathering on creep strains at multiple time points will be investigated and analyzed to determine the magnitude of damage to specimens from weathering. Modeling using the power law will also be conducted to calculate strain rates at specific time points. Results of flexure and creep experiments conducted on weathered specimens will be compared to results of non-weathered specimens in order to establish weathering effects.

MATERIALS AND METHODS

Material Preparation and Production

WPC specimens were produced for this study using two different formulations that were also used in a related study by Cameron (2009). Wood-fiber feedstock was the only difference between the two, with one being produced from 60 mesh White Pine flour (American Wood Fiber 6020BB), and the other from woody-biomass material (WBM) from a residential landfill used by Anchorage, Alaska homeowners. Further information on the material characteristics and processing procedures for these feedstocks can be found in the study by Cameron (2009).

Formulations consisting of 58% wood flour, 32% HDPE, 2% zinc stearate, 1% EBS wax, 5% talc, and 2% zinc borate were dry blended for approximately 10 minutes in a drum mixer and hand fed into a 35 mm counter rotating conical twin screw extruder (Cincinnati Milacron) at the Washington State University Composite Materials and Engineering Center. Mixtures were melt-blended at a constant barrel temperature profile of 177°C and extruded into rectangular 37 X 9.5 mm nominal cross sections at a 30 rpm screw speed, cooled in a water spray chamber, and cut into desired lengths. During extrusion, machine torque amps held constant at 11 amperes. Because the extruder was hand fed, melt pressure was not always constant, but held typically between 4100 and 5200 kPa. Specimens were planed down to a 6.35 mm thickness and cut to a 25.4 mm width in order to obtain a proper fit in the weathering device. A 14:1 span to width ratio was chosen for all flexure and creep specimens so that the entire test span length contained UV exposure. Therefore, specimens were cut to 114.3 mm lengths to allow for a test span of 88.9 mm and an overhang distance of 12.7 mm on each end of the supports.

Weathering of Specimens

Weathering of WPC specimens was conducted according to ASTM standards to create repeatable results. Irradiance was performed using an Atlas UV2000 Fluorescent UV/Condensation Weathering Device, while freeze-thaw cycling was accomplished using a simple tap water bath and temperature controlled freezer. Per ASTM D7032, one freeze-thaw cycle consisted of a 24 h water soak in tap water, a 24 h freeze at -29°C, and a 24 h thaw in ambient conditions (21°C, 50% RH). UV conditioning of specimens consisted of three segments per ASTM D6662:

1) 480 minutes of fluorescent UV light only with irradiance of 0.72 W/m^2 and black panel temperature of 70°C
2) 20 minutes of water spray with deionized water and no UV light
3) 220 minutes of condensation with no UV light

In order to establish the influences of weather on static flexure and long term creep testing of WPC specimens, the weathering schedule in Table 3.1 was used. It should be noted that for specimens containing both weathering types (UV and freeze-thaw), weathering was applied intermittently. For example, specimens weathered with 90 days of UV and 3 freeze-thaw cycles (Type VI) experienced 30 days of continuous UV exposure, then one freeze-thaw cycle, another 30 days of UV exposure, another freeze-thaw cycle, 30 final days of UV, then one last freeze-thaw cycle.

Table 3.1: Specimen weathering schedule

ID	UV (days)	Freeze-Thaw (# of cycles)
Type I	0	0
Type II	90	0
Type III	0	3
Type IV	30	1
Type V	60	2
Type VI	90	3

Testing Procedures

Static Flexure

Weathered and non-weathered WPC specimens were tested in flexure in accordance with ASTM D790 standards. This standard outlines a three-point bending setup in which specimens are supported at both ends and loaded at mid-span with a constant rate of deflection. Loading noses and supports were cylindrical surfaces with 12.7 mm diameters. The test span was based off a 14:1 length to nominal thickness ratio, yielding an 88.9 mm span from the 6.35 mm nominal specimen thickness. The testing apparatus used to load specimens was an electromechanical driven crosshead with a 10 KN load cell. A constant crosshead speed of 2.08 mm/min was applied to specimens until failure while load and mid-span deflection measurements were recorded using National Instruments LabVIEW 8.0 software at a collection rate of 2 Hz. Mid-span deflections were acquired using the crosshead extension. In order to gather information on material behavior, values of load-deflection were converted to stress-strain. Stress was found using the equation:

$$\sigma = \frac{3PL}{2bd^2} \qquad (1)$$

where: σ = stress in outer fibers (MPa)

P = load (N)

L = support span (mm)

b = width of specimen (mm)

d = depth of specimen (mm)

Strain was found using the equation:

$$r = \frac{6\Delta d}{L^2} \tag{2}$$

where: r = strain (mm/mm)

Δ = mid-span deflection (mm)

d = depth of specimen (mm)

L = support span (mm)

Specimen modulus of elasticity (MOE) was calculated from the slope of the stress-strain graph. The slope of the stress-strain graph was calculated for all specimens between the 10% and 40% of maximum stress in order to obtain MOE values from the elastic range of the curves per ASTM D790. Values of modulus of rupture (MOR) were found by calculating maximum flexural stress at point of specimen failure. For each weathering and wood feedstock type, six duplicate test specimens (72 specimens total) were used in order to obtain adequate information on strength and stiffness values.

Creep flexure

Weathered and non-weathered specimens were subjected to 14 weeks of flexural creep testing in order establish long term creep performance. Four duplicate specimens per weathering and feedstock type were used (48 total). Testing was performed using 88.9 mm test spans with 12.7 mm diameter cylindrical surfaced supports and loading noses. Specimen testing was performed in a temperature and humidity controlled room. Temperature was held constant at 21°C (+/- 2°C), while relative humidity remained at 71% (+/- 2%) Load frames were constructed using high strength laminated veneer lumber in order to avoid the influence of frame deformations on testing outputs. Frames were fitted with 12.7 mm outer diameter steel tubing to be used as specimen supports. Prior to testing, specimens were conditioned in the testing room under test conditions for a minimum of 48 hours.

Application of specimen loads were applied using a 50.8 mm long piece of 12.7 mm steel tubing fitted with high strength cable and an attached bucket with specified loads. Loads were applied by slowly lowering weighted buckets over the course of approximately 5 seconds until specimens were fully supporting the loads. Readings of mid-span deflections were taken using a dial gage attached to a steel plate supported by the same supports that specimens were resting on. Because loading noses were resting at the mid-span of each specimen, specimen mid-span deflections were taken by placing the dial gage on top of the loading nose, thus using the loading nose as a reference of specimen deflections. It should be noted that use of the dial gage did impart some loads onto specimens. The dial gage is spring loaded and applied approximately 4.5 N of force onto the mid point of specimens while measurements were taken. Before loads were applied, an initial dial gage reading was taken in order to obtain a pre-load measurement of dial gage extension. After loads were applied to specimens, initial deflection measurements were

determined by taking the difference between dial gage extension readings before and after application of loads. In order to eliminate variations between times of load application (i.e. time it took to lower buckets), "initial measurements" were taken exactly one minute after specimens were fully supporting the loads. Subsequent readings were taken at 3, 10, 60, 240, and 480 minutes after load application for each specimen. Daily measurements were taken for the following five days, followed by weekly measurements for the remainder of the 14-week period. Specimen deflections at each time point were calculated by taking the difference between dial gage extension readings prior to load application and at specific time period. Because of the large number of specimens for this study and the complicated logistics associated with creep loading, a reading of each specimen's deformation was taken at exactly 1, 3, 10, 60, 240, and 480 minutes after load application of that specimen, but at exactly 24 hours following the loading of the first specimen, a reading for that first specimen and all other specimens was taken. This is important because there is approximately a two hour time lapse between the loading of the first and last creep specimen. However, the time for each specimen measurement is adjusted to reflect the actual time of measurement after loading. This was done throughout the remainder of the 14 week loading duration.

Loads used for creep testing were based off a percentage of maximum stress experienced by specimens in static flexural testing. Loads were taken from stresses experienced by non-weathered specimens for each feedstock type so that specimens would experience the same stress level within their respective feedstock, regardless of weathering. A study by Pooler et al (2004) investigated, among other things, a threshold stress level for WPC specimens comprised of the same formulation used in this study. Short term creep tests were performed on specimens ranging from 30 to 90% of ultimate stresses. It was found that no damage occurred between 43

and 50% of ultimate strength, depending on temperature. A study by Brandt et al (2003) confirmed the findings of Pooler by performing 90 day creep tests on WPC specimens with the same formula at varying stress levels. Stress levels of 42.9% of ultimate strength was the lowest used on specimens and was the only ones that did not cause failure before the 90 day period had elapsed. Both the studies by Pooler and Brandt performed testing on deck board sized specimens and had no weathering applied to them. Therefore, for testing in this study, 30% of ultimate stress from flexure testing was conservatively chosen for creep specimens. This should be a more than adequate level to bring at least the non-weathered specimens to the full 14 week term of testing.

Strain versus time data was kept for each specimen during the entire 14 week duration of creep testing. Strain was calculated for each measurement using Eqn. 2 from the static flexure tests. Average strain versus time charts were created to compile duplicate specimen data and used to compare against other weathering and feedstock types.

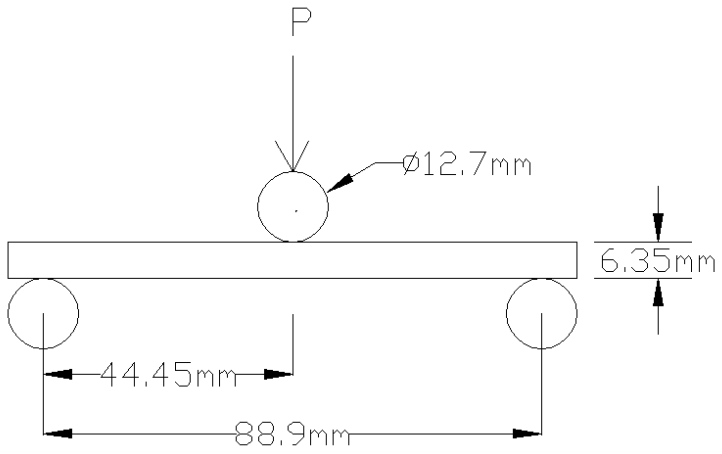

Figure 3.1: Schematic of static and creep flexure tests

Power law modeling

Using the strain versus time results from creep flexure testing, the viscoelastic nature of WPC specimens was modeled using Findley's power law. This simple yet effective model uses empirically found creep parameters to plot specimen strain versus time using the following formula:

$$\varepsilon_t = \varepsilon_o + at^m \tag{3}$$

Where ε_t is the creep strain at time t, ε_o is the instantaneous strain at application of load, a is the amplitude of transient creep, t is time, and m is the time exponent. For each specimen under creep loading, the creep strain at specific time points (ε_t), the instantaneous creep (ε_o), and time (t) are all known constituents, leaving the creep parameters a and m unknown. To quantify these parameters for each specimen, equation 3 is rearranged to:

$$\log (\varepsilon_t - \varepsilon_o) = \log a + m \log t \tag{4}$$

By plotting a log (ε_t - ε_o) versus log time graph, values of a and m can be acquired by fitting a linear best fit line to the specimen data. The slope of the best fit line yields the value of m while the y-intersect produces a value for log a. With creep parameters a and m, a continuous plot of specimen strain versus time can be generated. Depending on the level of fit (R^2 value from log (ε_t - ε_o) versus log time graph), specimen strain can be accurately calculated for any point in time. For each specimen, plots of strain versus time were generated using the power law as described in Equation 3. Also, results gathered from experimental creep tests were plotted on the same graphs to display the level of accuracy in using the power law model to predict creep behavior. Statistical comparisons were made to determine if weathering or feedstock type caused a significant difference in experimentally obtained strains at the initial 1 minute period, and at five, ten, and fourteen weeks.

Specimen strain rates can be calculated at any time by taking the first derivative of equation 3 with respect to time:

$$\delta\varepsilon/\delta t = a*m*t^{(m-1)} \quad (5)$$

This equation was used to calculate specimen strain rates at 1, 10, 100, 1000, 50000, 100000, and 150000 minutes of sustained creep loading for all specimens. This technique can be viewed as an easier and potentially more accurate method for determining strain rates as opposed to taking the straight line slope between two strain points. If the level of fit for the power model is high, the non-linear relationship between time and strain rate can be accurately calculated at any point in time, whereas the straight line method gives only an estimate of strain rate between two time points. Statistical comparisons were made to determine if weathering or feedstock type cased a significant difference in strain rates for each time period.

Statistics

Statistical analysis was performed to determine the significance of weathering and feedstock type on stiffness, strength, and strain to failure results obtained from static flexure testing. Analysis was also performed on results from creep specimen testing to determine the significance of weathering and feedstock type on strain and strain rates at specific time points in testing. An analysis of variance (ANOVA) was conducted to identify significance of difference between means at $\alpha = 0.05$. Comparison of means test was performed using Tukey's W procedure.

RESULTS AND DISCUSSION

Static Flexure

Results of static flexural testing are presented in Tables 3.2 through 3.4 and Figures 3.2 through 3.4. Strength, stiffness, and strain to failure values indicate a large influence associated with specimen weathering. Specimens weathered with freeze-thaw cycling only generally experienced a higher percentage of change in MOE, MOR, and strain to failure values from non-weathered specimens than specimens weathered with 90 days of UV light only.

Modulus of elasticity

For both feedstock types, MOE values significantly decreased with the application of all weathering types, as indicated in Table 3.2 and Figure 3.2. Considering the two weathering variables independently (freeze-thaw and UV), weathering with freeze-thaw cycling resulted in a 30% and 25% decrease in stiffness from control for pine and WBM specimens respectively, while a 19.8% and 18.1% decrease from control was experienced by specimens exposed to 90 days of UV light only. The decreases experienced by weathering pine and WBM specimens with UV and freeze-thaw cycling were large enough to be statistically significant. Previous studies have shown moisture to generally have the greatest affect on WPC properties (Lopez et al, 2004), therefore it is expected that the effects of UV light on specimen mechanical properties are much smaller than freeze-thaw cycling. Although the difference between weathering with UV and freeze-thaw cycling was quite large (12.8% and 8.4% for pine and WBM respectively), figures were not found to be statistically significant at a significance level of 0.05.

Coupled weathering had statistically significant effect upon stiffness properties when compared to control specimens. Weathering with 30 days of UV light and 1 freeze thaw cycle (type IV) decreased stiffness by 24.8% and 27.8% from control for Pine and WBM specimens respectively. For both feedstocks, an increase in the number of coupled weathering cycles resulted in further decrease of specimen stiffness values. As weathering of specimens progressed to type V and type VI (60 days UV/ 2 freeze-thaw cycles & 90 days UV/3 freeze-thaw cycles), Pine specimens experienced a 30.6% and 36.2% loss in stiffness, while WBM specimens lost 32.0% and 36.7% of their stiffness values for type V and type VI weathering, respectively. Results point to a decreased fiber/polymer matrix bond as coupled weathering of specimens is increased, explaining the corresponding loss in stiffness properties. These results were expected, as a study by Stark (2006) showed coupling of water spray and radiation was far more detrimental to stiffness properties than exposure to radiation only. It was hypothesized that that along with causing decreased bonding between the wood and fiber matrix because of swelling of wood fibers from moisture, the water spray also washed away the degraded surface layer, causing composites to become more vulnerable to further moisture penetration. Freeze-thaw cycling after extended exposure to UV light, as well as water spray cycles conducted during UV weathering, may wash away degraded surface material, making non-degraded material more susceptible to UV exposure and providing an easier pathway for further moisture penetration.

Coupled weathering exposure (Type IV, V, and VI) of all types resulted in a larger influence upon specimen stiffness than UV exposure only (Type II). These differences were statistically significant between Type II and Type VI weathering in Pine specimens, and between Type II and Types V and VI in WBM specimens. This is noteworthy because the difference in loss of stiffness properties between freeze-thaw cycling only (Type III) and coupled weathering

was not found to be statistically significant for either Pine or WBM specimens. Results are indicative of freeze-thaw cycling causing a majority of the deterioration in stiffness properties experienced by coupled weathering specimens.

Table 3.2: Weathering affect on average flexural stiffness with % change from control

Weathering ID	PINE MOE (GPA)	Change (%)	WBM MOE (GPA)	Change (%)
Type I	3.78 (8.1%)	-	3.39 (5.2%)	-
Type II	3.03^{A} (12.0%)	-19.8	2.77^{A} (7.1%)	-18.1
Type III	2.64^{AB} (11.9%)	-30.1	2.54^{AB} (7.3%)	-25.0
Type IV	2.84^{AB} (4.2%)	-24.8	2.45^{AB} (3.9%)	-27.8
Type V	2.62^{AB} (5.4%)	-30.6	2.30^{B} (4.9%)	-32.0
Type VI	2.41^{B} (11.3%)	-36.2	2.14^{B} (8.1%)	-36.7

Percent CV shown in ()
Means with the same letter are not significantly different at 95% level of confidence

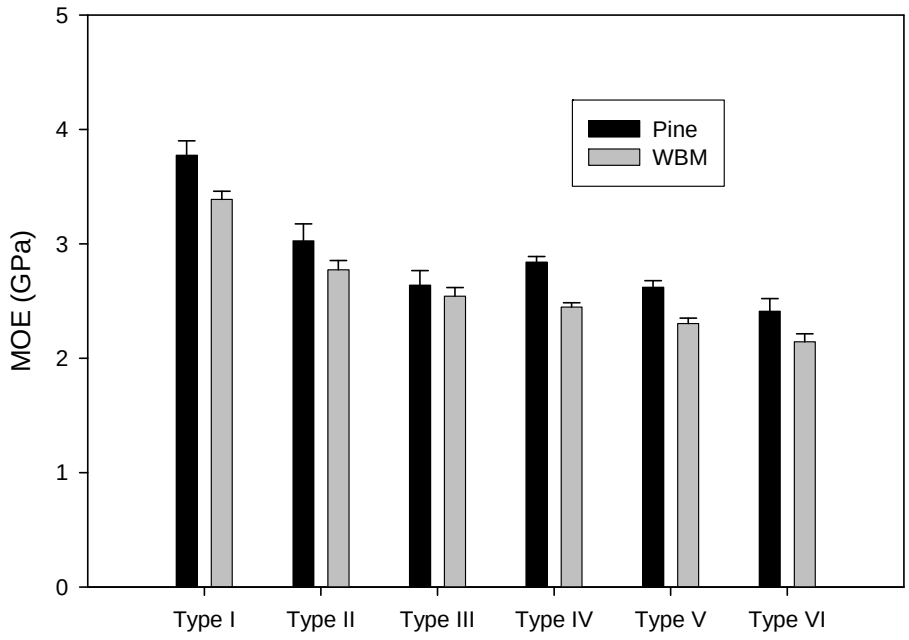

Figure 3.2: Graphical results of weathering affect on average flexural stiffness

Modulus of rupture

Results of strength values from flexural testing are displayed below in Table 3.3 and Figure 3.3. Weathering of WPC specimens resulted in a decrease of specimen strength for all weathering and feedstock types when compared to control samples. Analysis of variance results indicated statistically significant differences between effects of weathering on strength of WPC specimens. However, comparison of means analysis showed no statistical decrease in MOR and Type II weathering for pine specimens and Type II and III weathering for WBM specimens compared to their corresponding control specimens. These results correspond well with the study by Stark (2006), which also showed an insignificant influence of specimen strength properties exposed to irradiation.

For WBM feedstock composites, the affect of weathering on specimen strength seemed rather clear, as indicated by the progressive loss in properties as the amount of weathering was increased. Interestingly, Type II and III weathering produced similar results, both generating a 7.9% loss in strength values. This is in stark contrast to stiffness results, which saw much larger loss in properties with freeze-thaw cycling as opposed to UV exposure. However, as with strength values, differences between mechanical degradation in Type II and III weathering was not statistically significant. Ultimately, coupled weathering created a larger affect upon WBM strength than Type II and III weathering, with losses of 11.5%, 12.6%, and 18.0% for Type IV, V, and VI respectively. Although the differences were not statistically significant, an increase in weathering of specimens resulted in a subsequent decrease in strength.

The effect of weathering on the strength of Pine feedstock specimens, however, was not as clear. Independent weathering of specimens resulted in an 8.6% and 14.2% loss in strength for Type II and III exposure respectively. These results, although not statistically significant,

were expected, as freeze-thaw cycling has been shown in multiple studies to cause a greater decrease in mechanical bonding between the wood fiber and polymer matrix than UV exposure, which adversely affects the efficiency of stress transfer from matrix to fiber (Panthapulakkal et al 2006, Stark 2006). Coupled weathering caused significant damage to specimen strengths; however Type V weathering seemed to cause a slight increase in properties from Type IV, while Type VI weathering caused an average loss in strength higher than all weathering types. Although results appear erratic, it is important to note that coupled weathering of all types negatively affected specimen strength values and were not significantly different from each other.

Table 3.3: Weathering affect on average flexural strength with % change from control

Weathering ID	PINE MOR (MPA)	Change (%)	WBM MOR (MPA)	Change (%)
Type I	26.3^{A} (4.4%)	-	26.3^{A} (6.6%)	-
Type II	24.0^{AB} (3.5%)	-8.6	24.2^{AB} (5.9%)	-7.9
Type III	22.5^{B} (10.1%)	-14.2	24.3^{AB} (5.4%)	-7.9
Type IV	23.6^{B} (4.5%)	-10.3	23.3^{B} (4.0%)	-11.5
Type V	24.1^{AB} (3.2%)	-8.1	23.0^{B} (4.5%)	-12.6
Type VI	21.8^{B} (7.7%)	-17.0	21.6^{B} (2.1%)	-18.0

Percent CV shown in ()
Means with the same letter are not significantly different at 95% level of confidence

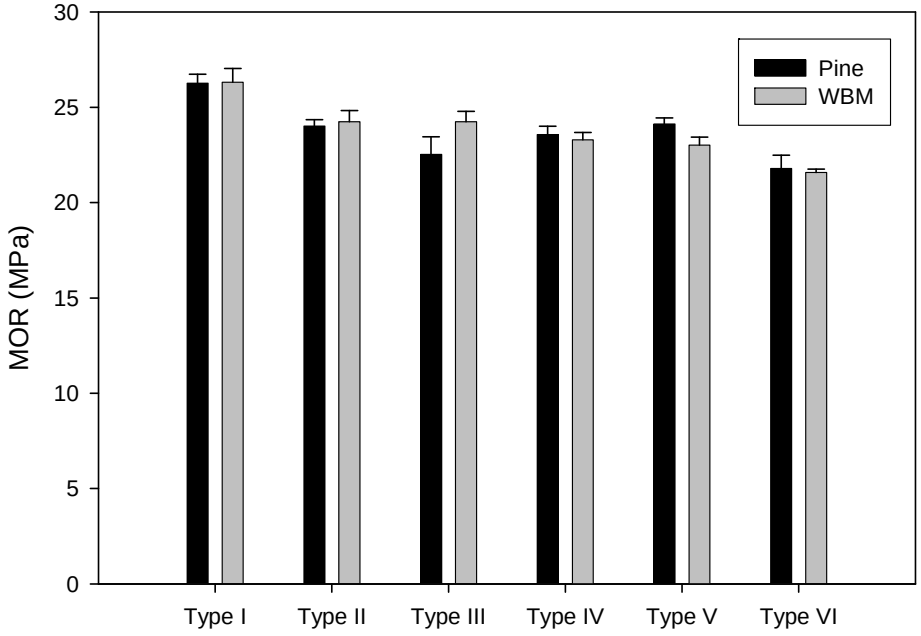

Figure 3.3: Graphical results of weathering affect on flexural strength

Strain to failure

Strain to failure was defined in this study as the flexural strain associated with the maximum load experienced by specimens during static flexure testing. All weathering conditions significantly increased strain to failure results for both feedstock types as displayed in Table 3.4 and Figure 3.4. Type III (freeze-thaw cycling only) caused higher strain to failure results than Type II weathering for Pine and WBM feedstock samples, with differences being statistically significant in Pine specimens. In general, Pine specimens experienced a higher influence of weathering upon strain to failure results than WBM. This could be a result of the larger particle size distribution in WBM specimens, as shown in the study by Cameron (2009). Hypothetically, a higher presence of fines in the fiber/polymer matrix could hinder the penetration of moisture beyond the composite surface due to better encapsulation and compounding of the fiber and thermoplastic matrix, allowing less degradation of mechanical

bonding and consequent increases in failure strains. Regardless of the influence upon fiber/polymer matrix, the affects of coupled weathering in Pine feedstock specimens were obvious, with increased strain to failures as weathering was increased from Type IV to Type VI. There was a statistically significant increase in strain to failures between Type VI and all other weathering types except III (freeze-thaw cycling), providing indication that freeze-thaw cycling was the main degradation element that caused increased strain to failures in flexure testing of Pine feedstock specimens.

However, WBM feedstock specimens did not display the level of influence on strain to failures from freeze-thaw cycling as Pine. Shown in Table 3.4, UV exposure (Type II) and freeze-thaw cycling (Type III) produced similar increases in strain to failures in flexure testing for WBM specimens. Where Pine specimens experienced increased strain to failures by an average of 51.6% with freeze-thaw cycling, WBM saw only a 28.9% increase. In coupled weathering, Pine displayed an increasing trend of strain to failures with increased weathering, denoted by the 36.2%, 37.1%, and 62.2% increases for Type IV, V, and VI weathering, respectively. WBM specimens, on the other hand, saw a 23.3%, 34.3%, and 27.1% increase from Type IV, V, and VI weathering. Again, this may be a result of the wider particle size distribution in WBM fibers, restricting the flow of moisture beyond composite surface during freeze-thaw cycling. Why the drop in strain to failure results from Type V to Type VI occurred is unknown, but differences are not statistically significant.

Table 3.4: Weathering affect on average flexural strain to failure with % change from control

Weathering ID	PINE STF (με)	Change (%)	WBM STF (με)	Change (%)
Type I	10486 (5.2%)	-	11011 (6.5%)	-
Type II	13016^{A} (11.1%)	+24.1	13523^{AC} (5.6%)	+22.8
Type III	15896^{BC} (10.1%)	+51.6	14199^{AB} (9.2%)	+28.9
Type IV	14277^{AB} (6.1%)	+36.2	13575^{AB} (5.1%)	+23.3
Type V	14372^{AB} (2.1%)	+37.1	14790^{B} (4.4%)	+34.3
Type VI	17008^{C} (7.3%)	+62.2	13993^{BC} (3.9%)	+27.1

Percent CV shown in ()
Means with the same letter are not significantly different at 95% level of confidence

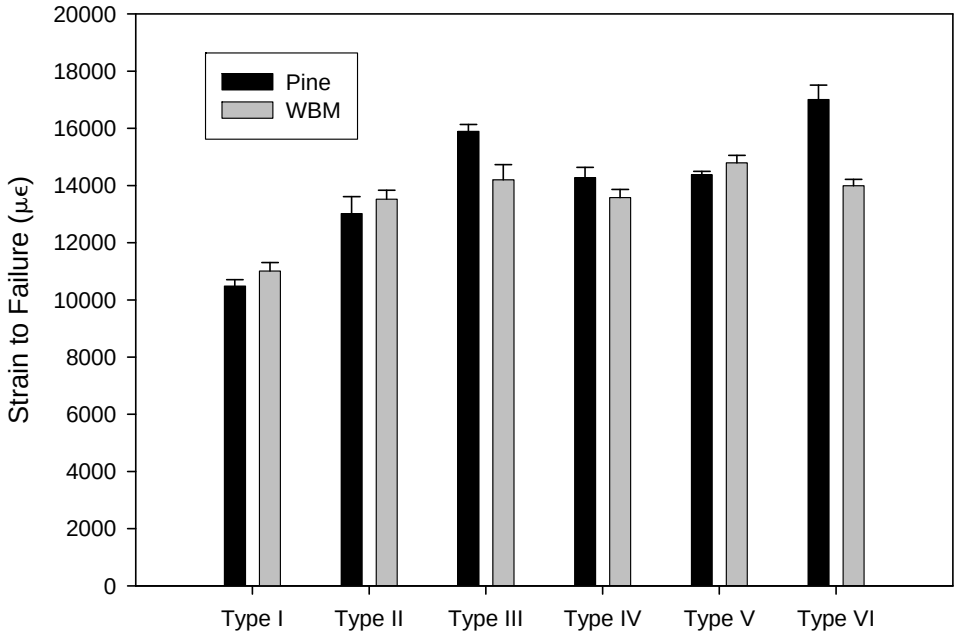

Figure 3.4: Graphical results of weathering affect on flexural strain to failure

Creep Flexure

Creep Strains

Table 3.5 and Figures 3.5 and 3.6 are average results of strains for Pine and WBM creep specimens at one minute and five, ten, and fourteen weeks after initial loading. All specimens maintained loads for the entire 14 week duration of testing without showing signs of tertiary creep. Statistical analysis found no significant difference between weathering types (Type I, III, and VI) in Pine specimens at any of the time periods, but it can be seen in Table 3.5 that there was a general trend of higher strains experienced by specimens with Type VI weathering than both Type I and III at all time periods. It was also found that Pine control and Type III weathered specimens experienced statistically significant higher levels of strain for all time periods than WBM control and Type III specimens. Slightly higher, but not significant, levels of strain existed for Pine specimens with Type VI weathering than with WBM specimens with Type VI weathering. These differences are slightly surprising considering Pine was found to have slightly higher (but not significant) values of stiffness in control, Type III, and VI weathered samples from static flexural tests performed in this study. Regardless, results indicate that Pine feedstock specimens creep more than WBM specimens, even at various levels of weathering

Samples produced with WBM feedstock exhibited creep strains after one minute significantly higher in specimens with Type III, IV, V, and VI weathering than control (Type I). Differences between weathering types were not significant at any of the other time periods, but, again, an apparent trend of higher creep strains in specimens with weathering than control existed at all time periods. Specimens with Type V weathering consistently experienced the highest level of creep strains while specimens with Type II (UV only) weathering, for the most

part, produced the lowest levels other than control (Table 3.5). It seems evident that UV exposure had a smaller affect on composite creep response for WBM specimens that freeze-thaw cycling. This hypothesis can be statistically proven only with initial one minute strain results, but results from this and multiple other studies have found UV exposure to produce far less damage to the mechanical bond in lignocellulosic/polymer composites in flexure tests (Stark 2006; Lopez et al. 2005; Panthapulakkal et al. 2006).

Table 3.5: Avg. specimen creep strains (με) at specific times and % change from control (Type I)

Weathering ID	WBM				PINE			
	1 min	5 weeks	10 weeks	14 weeks	1 min	5 weeks	10 weeks	14 weeks
I	2526 (9.2%)	7285 (4.2%)	8670 (4.4%)	9274 (5.1%)	3334 (12.6%)	11740 (22.2%)	13753 (22.0%)	14644 (21.3%)
II	3234 (5.5%)	8321 (4.2%)	9784 (2.3%)	10381 (3.8%)				
% Change	+28.0	+14.2	+12.8	+11.9				
III	3378 (1.7%)	8219 (9.3%)	10181 (7.9%)	10799 (8.4%)	3451 (11.9%)	11605 (23.7%)	13632 (24.8%)	14379 (24.8%)
% Change	+33.7	+12.8	+17.4	+16.4	+3.5	-1.2	-0.9	-1.8
IV	3536 (6.9%)	8544 (7.2%)	10373 (6.2%)	10937 (6.1%)				
% Change	+40.0	+17.3	+19.6	+17.9				
V	3874 (11.4%)	10467 (9.3%)	12380 (8.6%)	12981 (8.1%)				
% Change	+53.3	+43.7	+42.8	+40.0				
VI	3800 (2.1%)	9672 (1.1%)	11525 (1.0%)	12121 (0.5%)	3860 (5.6%)	12353 (9.1%)	14788 (8.2%)	15548 (8.1%)
% Change	+50.4	+32.8	+32.9	+30.7	+15.8	+5.2	+7.5	+6.2

Percent CV shown in ()

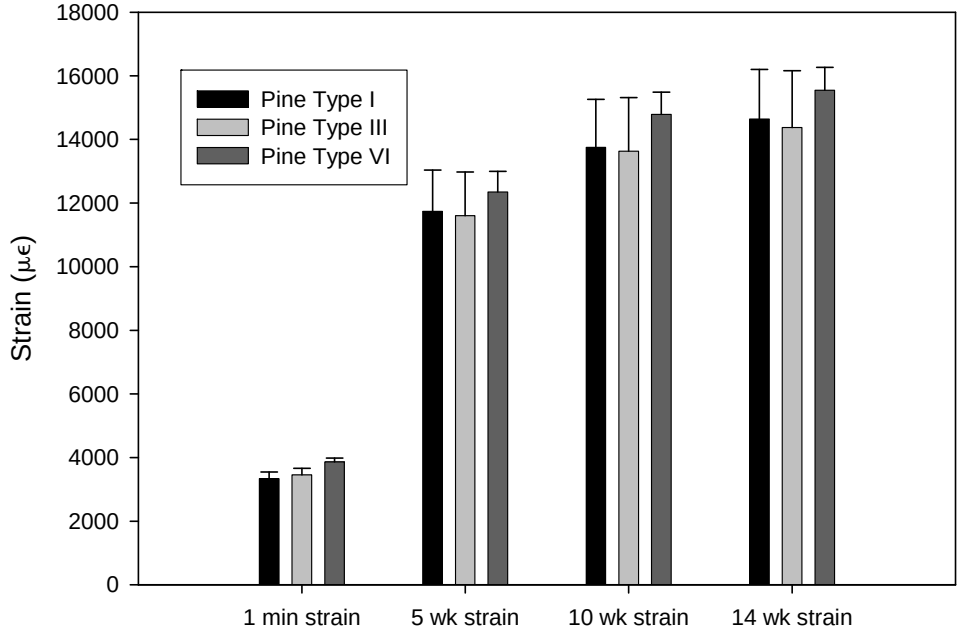

Figure 3.5: Graphical results of weathering affect on creep strain of Pine specimens at specific times

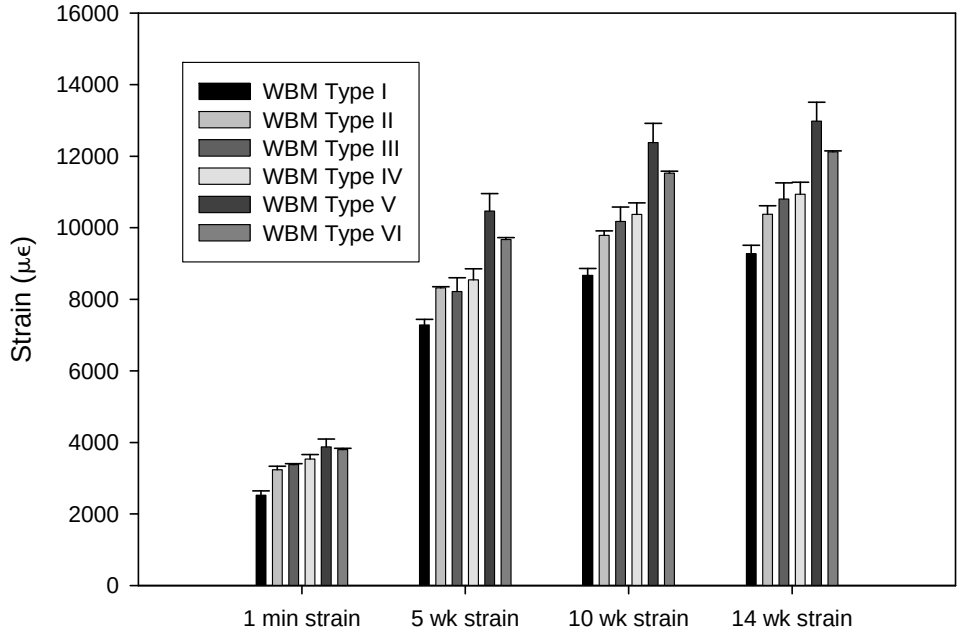

Figure 3.6: Graphical results of weathering affect on creep strain of WBM specimens at specific times

Although additional testing would be needed to properly confirm, it appears that weathering with freeze-thaw cycles caused increased creep strains over time in both Pine and WBM specimens. If confirmed, results would be in agreement with the findings of previous studies that investigated the effects of environmental conditioning on creep and static flexural behaviors of WPC's. In a study by Najafi S. et al. (2008), results found that increases in creep strain was a result of corresponding increases in specimen submersion time in water baths prior to testing. The presence of moisture in specimens was concluded to have two contributions to WPC creep properties. The first is that moisture exposure increases initial creep strains. In a study by Ebrahimi et al. (2003), it was found that creep strains in WPC's are mainly controlled by the elastic modulus of the composite. So two different composites will exhibit similar creep rates over time, but initial strains will differ depending on elastic modulus (statics). Therefore, specimens conditioned with higher levels of moisture will have lower elastic moduli and subsequent larger initial deflections (strains) at equal stress levels. The second contribution to creep parameters from water penetration is the debonding of the fiber/polymer matrix and subsequent relaxation of molecules, resulting in higher strains over time.

Considering freeze-thaw cycling has been shown in multiple studies, including this one, to lower the elastic modulus of WPC's, it would be expected that weathered specimens would show increased levels of strains compared to control specimens with the application of test loads. As previously discussed, weathering had a statistically significant affect on WBM specimen one minute strains (first reading), but not during the other time points, corresponding well with the findings in the study by Ebrahimi et al. (2003). Although results were not statistically significant, it also appears that as cycles of coupled weathering were increased, so were corresponding strains at all investigated times. This is expected, as increased weather cycling

has been shown in this study to decrease mechanical properties of composites in static testing. Along with the affects on initial strain, the debonding and material degradation associated with freeze-thaw cycling and UV exposure would be expected to cause relaxation of molecules and higher strains at extended periods. Again, this was found to be true, although not statistically significant, in this study.

Power Law Modeling/Strain Rates

Empirical creep parameters *a* and *m* were acquired so that the long term response of each specimen could be modeled using Findley's Power Law. The linear best line fitted with the data described in equation 4 exhibited a very high correlation, denoted by the average R^2 values displayed in Table 3.6. Results indicate that the power law is an effective means for modeling the creep response of WPC specimens in this study, as was also found in various other studies (Kobbe 2005; Najafi A. et al 2008; Sain et al 2000). Figures 3.7 through 3.8 show experimental results of flexural creep strain testing for each weathering and feedstock type plotted with the associated power law model over time, and further iterate the effectiveness of using Findley's Power Law to model WPC creep strains over time.

Table 3.6: Avg. R^2 values from linear best fit line fitted to specimen creep strains using equation 4

Weathering ID	Average R^2
Pine Type I	0.90 (7.5%)
Pine Type III	0.96 (2.4%)
Pine Type VI	0.96 (3.2%)
WBM Type I	0.91 (7.1%)
WBM Type II	0.96 (0.1%)
WBM Type III	0.95 (5.6%)
WBM Type IV	0.97 (2.5%)
WBM Type V	0.97 (2.6%)
WBM Type VI	0.92 (4.8%)

Percent CV shown in ()

Given its effectiveness, other parameters, such as creep strain rate, can be confidently calculated using the fundamentals of Findley's Power Law. Using equation 5, the average creep strain rates of each specimen were calculated at 10, 100, 1000, 50000, 100000, and 150000 minutes after initial loading and are displayed below in table 3.7. Statistical analysis found no significant difference in strain rates between any of the weathering or feedstock types at any of the investigated time periods. In the study by Ebrahimi et al. (2003), it was determined that the creep response of WPC specimens is mainly controlled by the elastic modulus of the composite. Therefore, the only affect weathering has is on the instantaneous creep of specimens, and has little to no affect upon creep strain rates over time; correlating well with the findings of this study.

Table 3.7: Avg. creep strain rates (με/minute) with % change from control (Type I)

Weathering ID	1m	10m	100m	1000m	50000m	100000m	150000m
Pine Type I	112.4 (25.9%)	21.9 (24.6%)	4.27 (25.3%)	0.835 (27.6%)	0.0526 (33.4%)	0.0322 (34.6%)	0.0242 (35.3%)
Pine Type III	122.9 (69.2%)	22.8 (55.7%)	4.31 (42.7%)	0.828 (30.9%)	0.0523 (19.3%)	0.0322 (19.4%)	0.0243 (19.8%)
% Change	+9.3	+4.4	+1.0	-0.8	-0.5	+0.0	+0.3
Pine Type VI	92.6 (44.4%)	17.8 (36.1%)	3.44 (26.9%)	0.670 (16.8%)	0.0424 (3.0%)	0.0261 (6.1%)	0.0196 (8.1%)
% Change	-17.6	-18.6%	-19.3%	-19.7%	-19.3%	-19.1%	-19.0%
WBM Type I	104.4 (33.8%)	16.9 (23.2%)	2.77 (12.1%)	0.457 (2.9%)	0.0220 (21.5%)	0.0129 (25.4%)	0.0094 (27.6%)
WBM Type II	88.5 (18.5%)	15.9 (13.0%)	2.88 (7.5%)	0.521 (4.3%)	0.0288 (12.0%)	0.0172 (13.9%)	0.0128 (15.0%)
% Change	-15.2%	-5.8%	4.0%	14.0%	30.7%	33.5%	35.2%
WBM Type III	69.2 (61.2%)	12.9 (55.1%)	2.45 (44.9%)	0.481 (28.2%)	0.0346 (25.0%)	0.0222 (36.5%)	0.0172 (43.5%)
% Change	-33.7%	-23.8%	-11.5%	5.1%	57.1%	72.3%	82.6%
WBM Type IV	88.0 (26.2%)	15.8 (20.3%)	2.85 (15.4%)	0.514 (12.2%)	0.0283 (12.7%)	0.0169 (13.4%)	0.0125 (14.0%)
% Change	-15.7	-6.6	+2.9	+12.4	+28.3	+31.0	+32.6
WBM Type V	152.1 (40.0%)	24.2 (28.4%)	3.90 (17.3%)	0.633 (8.3%)	0.0295 (15.0%)	0.0172 (17.7%)	0.0125 (19.4%)
% Change	+45.7	+43.2	+40.8	+38.4	+34.1	+33.3	+32.8
WBM Type VI	110.3 (18.3%)	19.3 (12.0%)	3.40 (5.1%)	0.600 (2.3%)	0.0319 (15.8%)	0.0190 (18.3%)	0.0140 (19.8%)
% Change	+5.6	+14.3	+22.9	+31.3	+44.7	+46.9	+48.2

Percent CV shown in ()

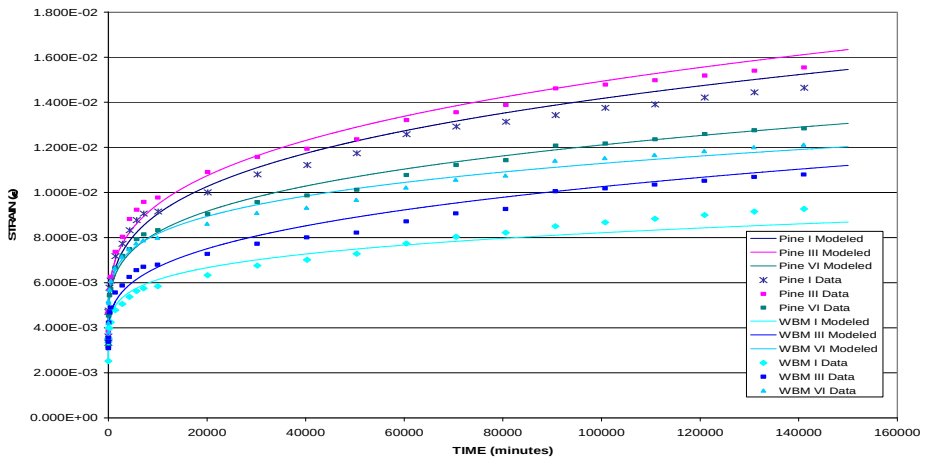

Figure 3.7: Average experimental and modeled strain versus time comparison for Pine and WBM specimens

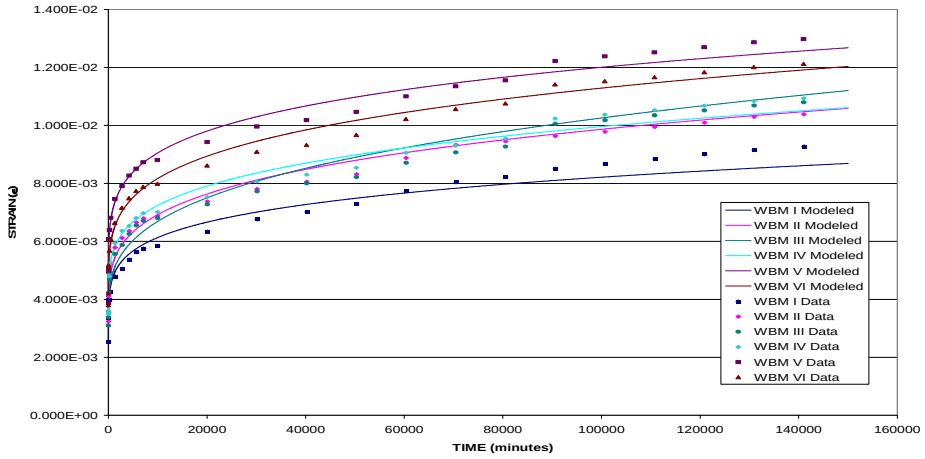

Figure 3.8: Average experimental and modeled strain versus time results for WBM specimens

CONCLUSIONS

The effects of weathering on the static and creep flexural responses of wood fiber/thermoplastic composites were investigated. The following can be concluded from the experimental results of this study:

- Weathering of wood plastic composites with freeze-thaw cycling and UV exposure significantly influences strength, stiffness, and strain to failure properties. This is thought to be a result of the degradation of the wood fiber/polymer mechanical bond that occurs with such weathering.

- Coupled weathering was found to posses a larger influence upon composite static flexural properties than independent weathering with freeze-thaw cycling and UV exposure. Although both types of weathering were found to influence properties, freeze-thaw cycling had the largest affect during coupled weathering.

- Weathering of WPC causes significant increases in flexural creep strain, especially within the first minute of sustained loading. This is believed to occur as a result of the large influence weathering has upon static response of composites. Consequently, increases in creep strain after one minute and creep strain rates from weathering were not found to be statistically significant.

- Although not statistically significant, coupled weathering of specimens appeared to have a larger influence upon creep strains than independent weathering with freeze-thaw cycling and UV exposure. More research is testing is needed to confirm such results.

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CHAPTER FOUR: PROJECT SUMMARY AND CONCLUSIONS

Summary and Conclusions

In recent years, the Alaskan forest products industry has suffered considerably with mill closures, tougher environmental regulations, and a decline in demand from Pacific-rim countries. However, an investment in the production of wood-plastic composites (WPC) using low value, urban woody biomass material as feedstock could prove profitable and help rebuild a struggling Alaskan economy. The goal of this study was to develop and demonstrate that commercially viable wood plastic composite products can be produced using low-value waste streams from secondary industry and woody biomass from urban wood waste lots. Because of the harsh environmental exposures such products would experience in Alaska, further understanding of how environmental exposure influences mechanical properties, as well as viscoelastic response, was also investigated.

In the first part of the study, experiments characterizing raw material and extruded composite physical performance were conducted; the results of which were compared to widely used pine feedstock under the same experiments. Particle size analysis of raw materials indicated a wider particle size distribution in birch and especially WBM samples relative to pine. Statistically lower diffusion coefficients associated with Alaskan material were also found during water soak testing. However, mechanical testing of specimens found no statistical difference in flexural strength, stiffness, creep recovery, or fastener withdrawal tests between any of the feedstock types. As a result, WPCs made with the two Alaskan low-value woody materials should be considered a viable option for the Alaskan forest products industry.

To investigate the influence of environmental exposure upon WPC products, pine and WBM feedstock specimens were planed down and exposed to a combination of ASTM

conditioning protocols consisting of ultra violet light exposure and freeze-thaw cycling. Once conditioned, specimens were subjected to static flexure and long term (90 day) creep testing to determine the influence of coupled weathering on mechanical performance. Static flexure results indicated a significant influence of weathering of specimens upon values of strength, stiffness, and strain to failure. It also appeared the coupled weathering created larger influences upon flexural properties than independent weathering. However, results suggest that freeze-thaw cycling had a significantly larger affect than UV exposure. Weathering of WPC caused significant increases in flexural creep strain as well, especially within the first minute of sustained loading. This is believed to occur as a result of composite MOE having the largest affect on creep response. Consequently, increases in creep strain after one minute and creep strain rates from weathering were not found to be statistically significant. Although not statistically significant, coupled weathering of specimens appeared to have a larger influence upon creep strains than independent weathering with freeze-thaw cycling and UV exposure.

Recommendations

Based upon the results of testing in this study, the following is recommended for further investigation:

- To further understand the fiber characteristics of the Alaskan birch and WBM feedstocks, a scanning electron microscope (SEM) should be used to examine aspect ratios and integrity of fiber cell walls after milling.

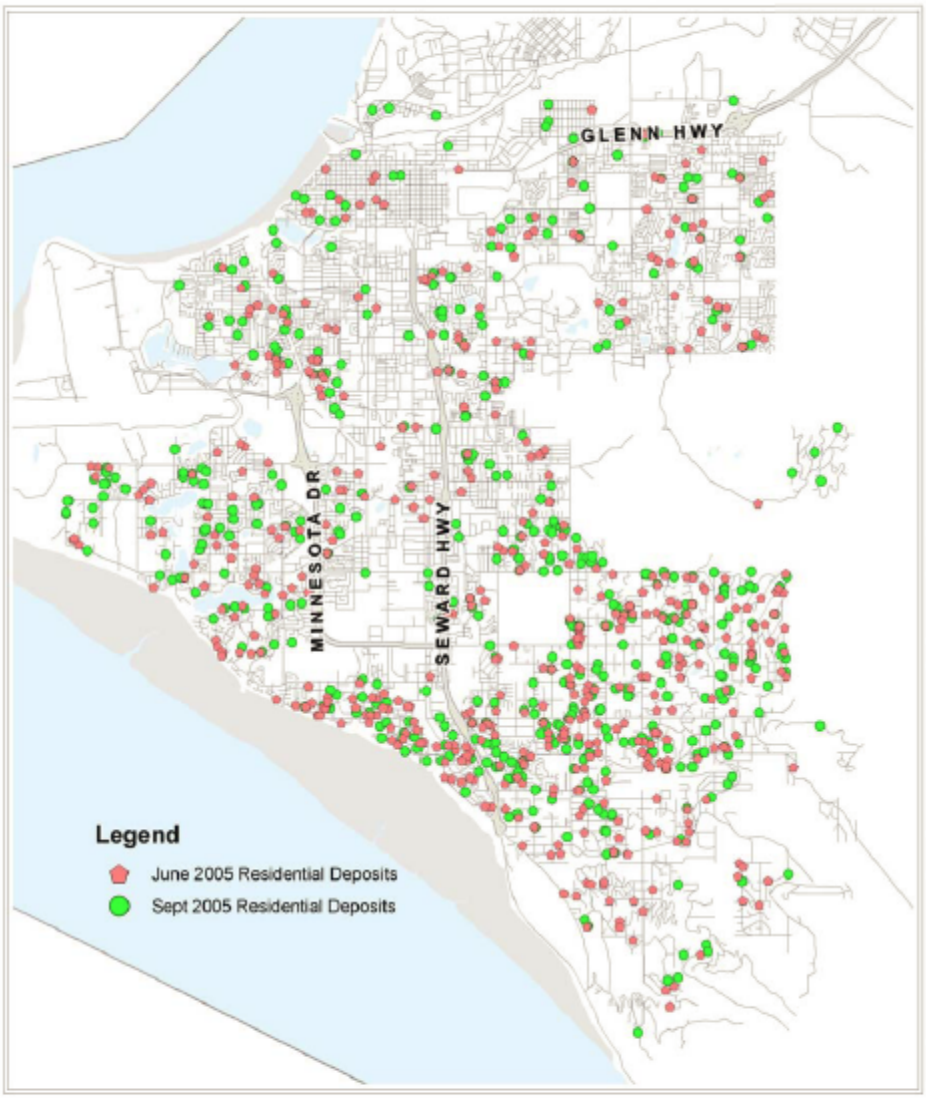
- Using a SEM, further investigation of the degradation of the fiber/polymer bond in composites exposed to weathering should be performed to gain a better understanding of the influence of coupled weathering on static flexural and creep performance.

- Creep testing with a higher number of replicate specimens and more combinations of weathering cycles should be performed to gain a concrete understanding of the influence of weathering on the creep response of WPCs.

APPENDIX A

Information on source and species of urban woody biomass material (WBM)

Figure 12. Source Locations, Woody Debris, Anchorage Woodlot.



N W E S

Anchorage Woodlot Use

Anchorage Soil and Water Conservation District

northerneconomics inc.

6.2 Anchorage Woodlot Statistics

The District requested information on Woodlot usage, including species, volumes, potential chip (mulch) volumes, and weights.

6.2.1 Input Assumptions, all Years

Site inspections at the Woodlot, along with discussions with residents, attendants, and subcontractors generated answers for the District's questions.

Volumes are approximately 50:50 conifers (spruce) to hardwoods (birch, cottonwood, alder, other). Species weights were developed from test sites on the Anchorage Hillside as well as the Kenai Peninsula; spruce debris was considered dry and had an input weight of 28 pounds per cubic foot of solid wood. Birch, cottonwood, alder and other woods were evaluated at 55 pounds per cubic foot of solid wood (birch) or 50 pounds per cubic foot, solid wood basis (all other species).

The average calculated volume per load was 1.9 cubic yards, based on weights, end-of-year mulch volumes, and discussions with staff.

Discussion with Hillside residents, plus experience of project staff, mapping, and tract size analysis, suggested an average acreage per load of 0.3 and these numbers were felt to be representative, but conservative.

6.2.2 Results, 2005

Results for 2005 are summarized in Table 13 for the 7,325 loads that were counted during the April to September seasons.

Table 13. Woodlot Use by Species, Volume, and Weight, 2005.

Species	*Est. Percent*	*Chips, CY*	*Chips, CF*	*Weight, Lbs*	*Tons*
Spruce	50%	7,000	189,000	1,924,364	962
Birch	35%	4,900	132,300	2,646,000	1,323
Cottonwood	5%	700	18,900	343,636	172
Alder	5%	700	18,900	343,636	172
Other	5%	700	18,900	343,636	172
Total	100%	14,000	378,000	5,601,273	2,801

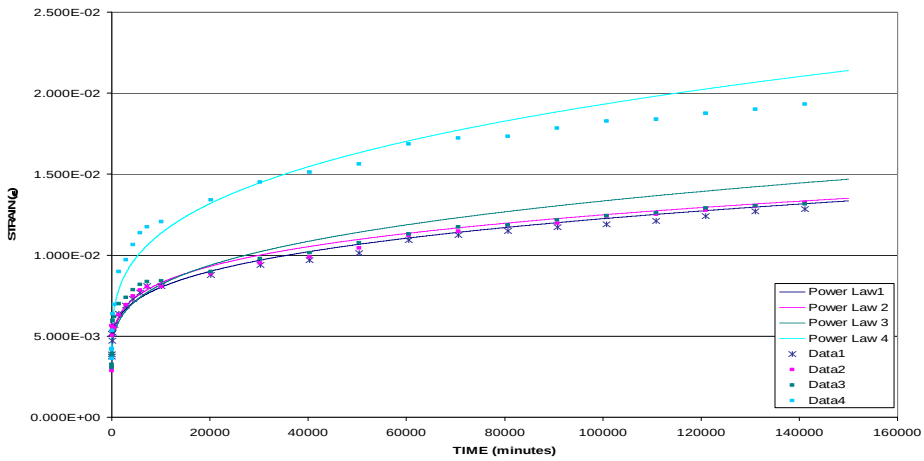
Source: Northern Economics

APPENDIX B

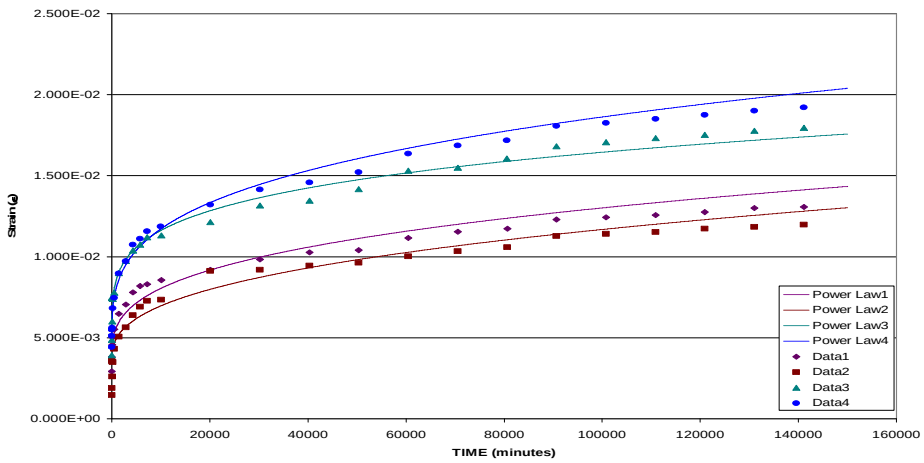
Power law coefficients, trend-line fit, and experimental creep graphs

$$\varepsilon_t = \varepsilon_o + at^m$$

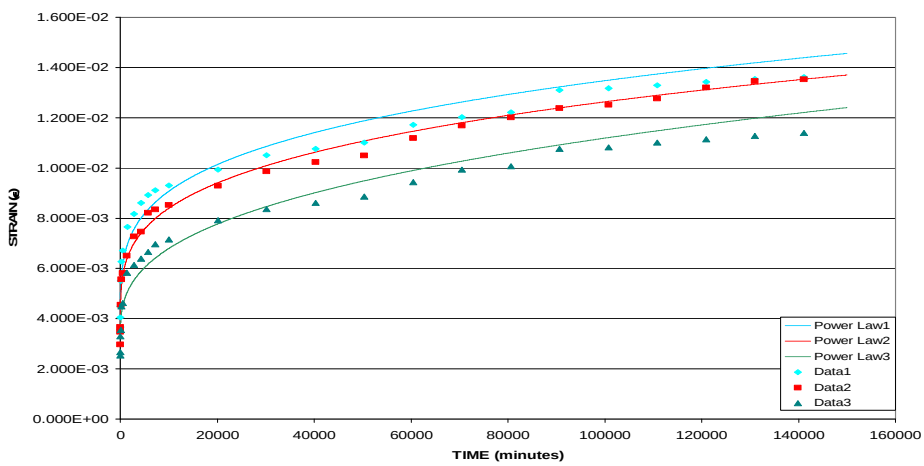
SPECIMEN	ϵ_o (ϵ)	m	a	R^2
PBC1	0.00375	0.300	2.70E-04	0.897
PBC2	0.00289	0.250	5.41E-04	0.814
PBC3	0.00308	0.304	3.12E-04	0.924
PBC4	0.00363	0.308	4.52E-04	0.976
PFTC1	0.00355	0.324	2.27E-04	0.958
PFTC2	0.00355	0.377	1.06E-04	0.958
PFTC3	0.00392	0.212	1.09E-03	0.934
PFTC4	0.00442	0.290	5.06E-04	0.991
PUVFTC3-1	0.00367	0.259	4.96E-04	0.959
PUVFTC3-2	0.00366	0.278	3.66E-04	0.985
PUVFTC3-3	0.00329	0.353	1.35E-04	0.924
SBC1	0.00263	0.197	6.08E-04	0.820
SBC2	0.00280	0.288	2.22E-04	0.932
SBC3	0.00227	0.167	8.66E-04	0.901
SBC4	0.00240	0.230	3.88E-04	0.972
SUVC1	0.00329	0.237	4.12E-04	0.960
SUVC2	0.00337	0.290	2.39E-04	0.962
SUVC3	0.00303	0.248	3.96E-04	0.962
SFTC1	0.00340	0.541	1.25E-05	0.870
SFTC2	0.00342	0.269	3.43E-04	0.980
SFTC3	0.00340	0.242	4.07E-04	0.981
SFTC4	0.00330	0.274	2.90E-04	0.971
SUVFTC1-1	0.00368	0.265	3.52E-04	0.942
SUVFTC1-2	0.00318	0.220	5.35E-04	0.987
SUVFTC1-3	0.00372	0.276	2.73E-04	0.986
SUVFTC1-4	0.00356	0.273	2.40E-04	0.948
SUVFTC2-1	0.00348	0.265	3.52E-04	0.942
SUVFTC2-2	0.00449	0.208	8.04E-04	0.990
SUVFTC2-3	0.00366	0.148	1.56E-03	0.950
SUVFTC2-4	0.00386	0.238	4.92E-04	0.989
SUVFTC3-1	0.00391	0.222	5.71E-04	0.981
SUVFTC3-2	0.00379	0.235	5.06E-04	0.911
SUVFTC3-3	0.00376	0.238	4.82E-04	0.876
SUVFTC3-4	0.00373	0.295	2.75E-04	0.911



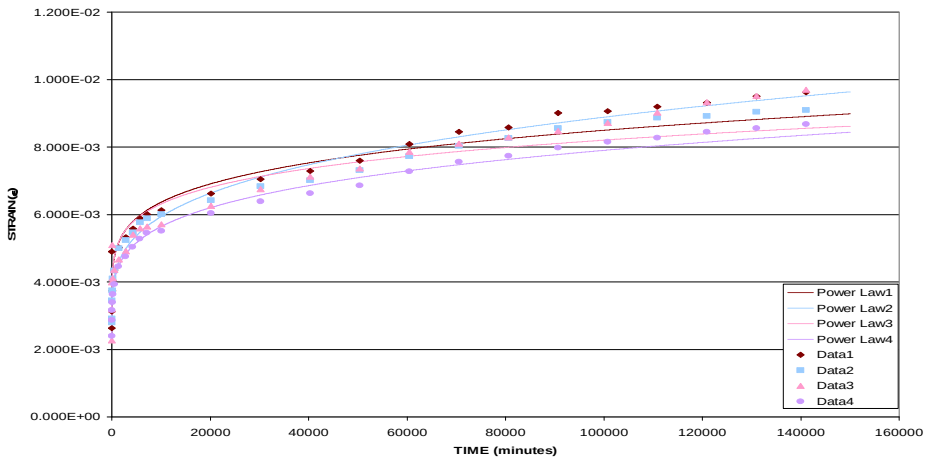
Experimental and modeled strain versus time results for Pine Type I



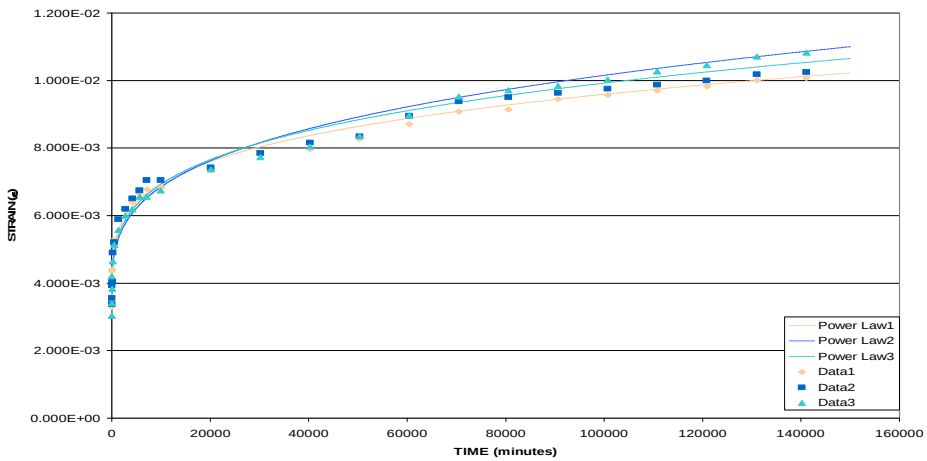
Experimental and modeled strain versus time results for Pine Type III



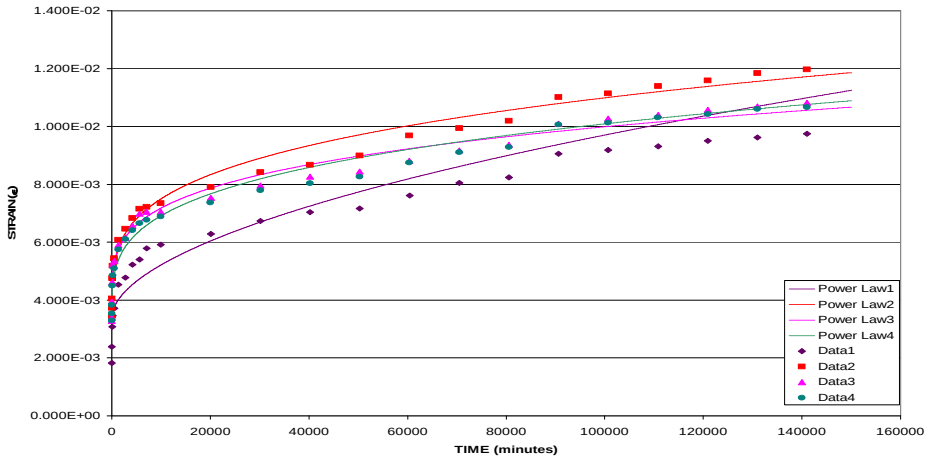
Experimental and modeled strain versus time results for Pine Type VI



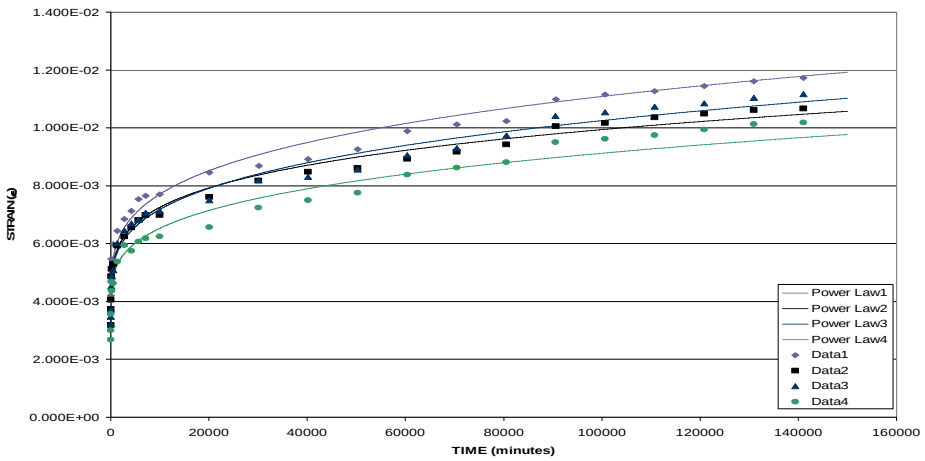
Experimental and modeled strain versus time results for WBM Type I



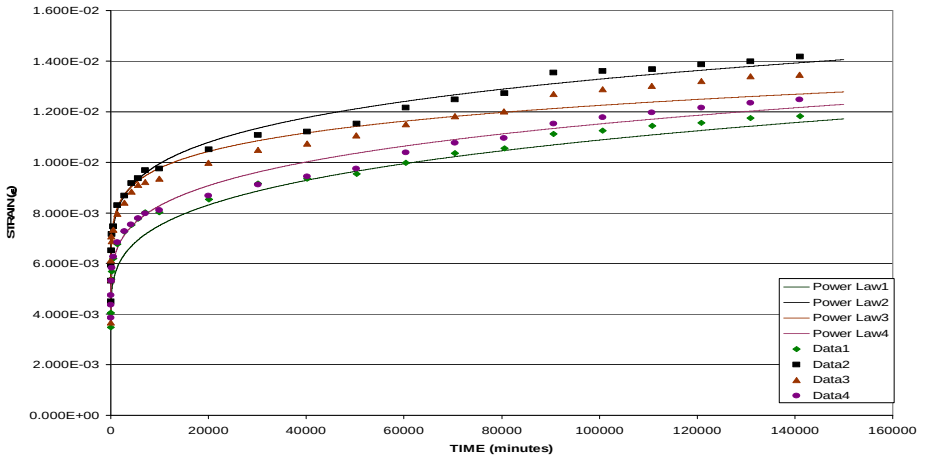
Experimental and modeled strain versus time results for WBM Type II



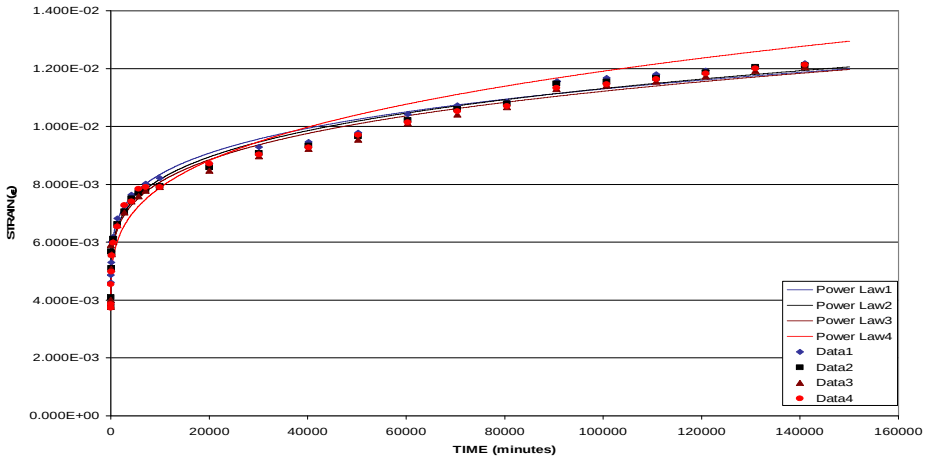
Experimental and modeled strain versus time results for WBM Type III



Experimental and modeled strain versus time results for WBM Type IV



Experimental and modeled strain versus time results for WBM Type V



Experimental and modeled strain versus time results for WBM Type VI