

ENGINEERING CHARACTERISTICS OF RECYLED PLASTIC PIN, LUMBER  
AND BAMBOO FOR SOIL SLOPE STABILIZATION

by

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ABSTRACT

ENGINEERING CHARACTERISTICS OF RECYLED PLASTIC PIN, LUMBER  
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Shallow slope failures are predominant in North Texas and pose a significant maintenance problem. The traditional slope repair and stabilization techniques become expensive in some instances with direct costs associated in maintenance and repair of landslides. A new approach for slope stabilization has been developed using Recycled Plastic Pins ( RPP) to stop slope movements. The engineering properties of RPP in compression and bending strength along with environmental considerations dictate the design and repair of slopes using RPP. Two other materials have also been considered as an alternative: (1) Wood lumber and (2) Bamboo. Wood has many advantages as an engineering material. It is strong, light, and fairly simple to work with. Bamboo is typically thought of for decoration is recently becoming more popular as a structural element. Bamboo is one of the fastest growing plant in the world and readily available in developing countries like: South Asia. However, to administer their application in slope stabilization, it is necessary to have a clear understanding of their structural behavior under in situ conditions.

The current study focuses on determining engineering properties of Recycled Plastic Pins (RPPs), wood lumber and bamboo and their applicability in soil slope stabilization. The RPPs, manufactured by Bedford Technology Ltd., was collected from Minnesota, the bamboo samples were collected from Benson Tropical Sea Imports and the wood lumber was collected from local stores . An extensive experimental program was developed to determine the engineering characteristics of these materials. The tests that were performed were the flexure test and the uniaxial compression as they govern to match the field load orientation. Three different strain rates were applied during the test were based on the ASTM standards and field conditions. For each strain rate, three samples from each of the respective specimen were taken. Three different environmental conditions, to match the Texas soil, were considered for the current study, 1) Acidic condition of a pH of 5.5 representing Texas red clay 2) Alkaline condition of a pH of 8.5 representating Texas black clay 3) Neutral condition of a pH of 7.0 simulating rainwater and moist conditions in field.

The test results showed that wood possess highest peak strength, both in flexure and compression, but RPPs extended to accommodate more soil movments, which was upto 19% in compression at the lowest strain rate. However, the strength of wood and bamboo were decreased by 50% for wood and 65% for bamboo under different environmental conditions where the strength reduction for RPPs was only 8%. The results, both the flexure and the axial compressive tests in environement and non-environment conditions, reflect that RPPs could be utilized over wood and bamboo to stabilize slope failures in field conditions. However, for the solid condition with a pH of 7.0, all three materials can be used for slope stabilization.

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## CHAPTER 1

### INTRODUCTION

#### 1.1 Background

Natural disasters due to slope failure present an important threat all over the world. Each year, rain induced slope failures cause significant damages in infrastructures and environments, as well as tragic losses of human lives around the world. Currently, the use of Recycled Plastic Pin (RPP) to stabilize shallow slope failure offers a great economic and construction benefit and has marked a notable recognition in the engineering community. Plastic pin driven into the slope face crossing the slip surface provides an additional resistance force along the slip plane thus increasing the factor of safety, as showed in Figure 1.1. RPPs are fabricated from recycled plastics and other waste materials (polymars, sawdust, fly ash) that reduce the waste volume entering the landfill. Due to its constituent materials, RPPs are eco-friendly and cost-effective and offers great biotic and abiotic resistance.

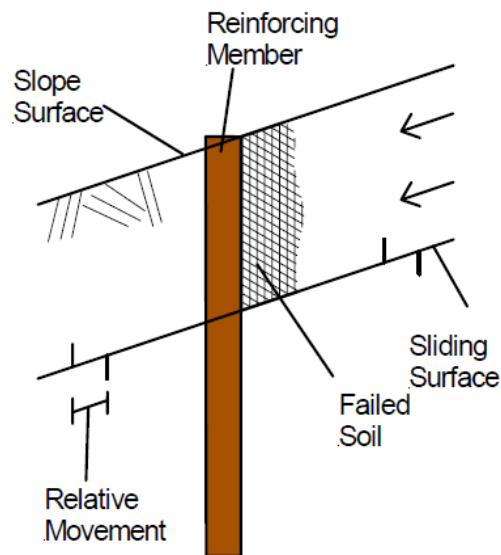


Figure 1.1 : Slope Stabilization by Reinforced Plastic Pins (Sommers et al., 2000)





Figure 1.2: Recycled Plastic Pins (RPPs)

Due to endless variety of possible constituents from waste and manufacturing processes, the resulting recycled plastic products offers different engineering properties, even among similar produced materials and sections. In order to be implemented in the field, it is important to understand the nature of the load orientation and possible effect on the engineering behavior. Considering in situ phenomena, flexure and uniaxial compression test are suited to get hands on the field behavior of the bearing specimen ( Bowders et al., 2003). Based on the field movements, the strain effects can be incorporated in the test and on-site peak strength with the modulus of elasticity can be established. Figure 1.3 shows a typical stress-strain curve for RPPs, in flexure.

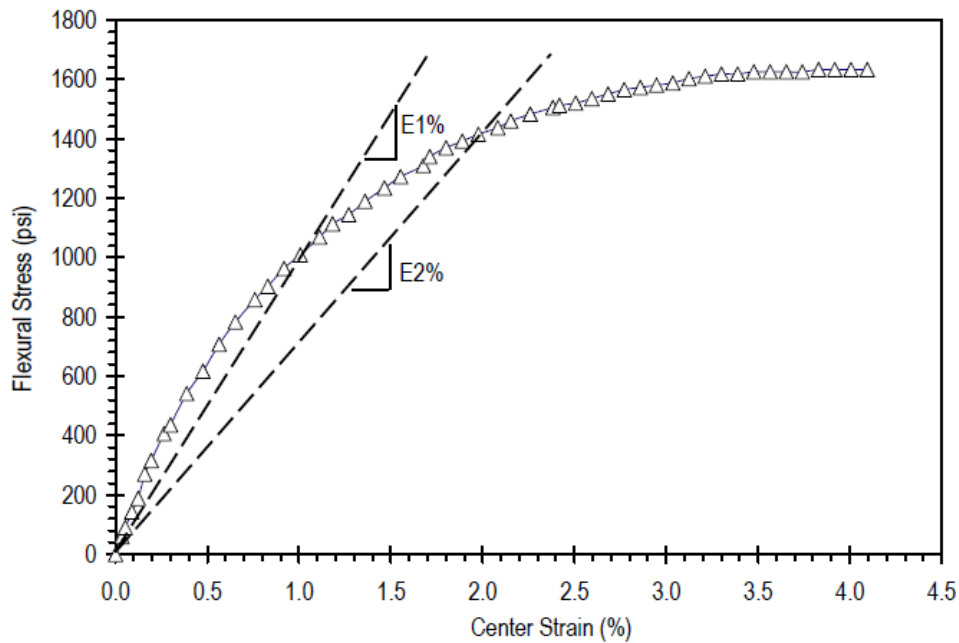


Figure 1.3: Typical Stress-Strain curve for RPPs in flexure ( Bowders et al., 2003)

Due to local availability and abundance in production, wood has been used for many decades as a potential structural material for homes, bridges, etc. The benefits of using wood are financially worthwhile, aesthetically acknowledged and environmentally friendly. Another potential structural building material, bamboo has proved to be viable as bearing associate. The resistive action from their elastic fiber is very good and in some cases, the compressive strength of bamboo is same as wood.



Figure 1.4 : Wood



Figure 1.5: Typical Bamboo Plant ( Bamboo Technology, 2010)



Figure 1.6: Prepared Bamboo Samples

Analysis regarding the application of wood and bamboo over RPP in slope stability analysis has not yet been performed. Therefore, to use them for slope stabilization, the following needs to be investigated,

- ✚ Determining the basic engineering and material properties of wood and bamboo
- ✚ Determining the potential variability of these properties to that of RPPs with different strain rates
- ✚ Determining how these materials behave when subjected to various potentially detrimental environments.

### 1.2 Research Objectives & Tasks

The objective of the current study was to determine the basic engineering properties, which can be associated with slope failure, of RPP, wood and bamboo at different strain rates. Also, the effect of different environmental conditions on the engineering characteristics of RPP, wood lumber and bamboo were studied. The specific tasks that were accomplished in the current study is presented here:

- (i) Conducted a flexural analysis of RPP, Wood and Bamboo at specified strain rates.
- (ii) Conducted uni-axial compressive tests on RPP, Wood and Bamboo at specified strain rates.
- (iii) Applied environmental restraints, based on local conditions, on RPP, Wood and Bamboo.
- (iv) Determined the stress-strain behavior (peak strength and the modulus of elasticity) in the specified conditions in each test.
- (v) Compared the performances of RPP, wood lumber and bamboo as which of the three perform more consistently in adverse situations.
- (vi) Recommended most suitable material for slope stabilization.

### 1.3 Organization of the study

A summary of the organization of the current study is abridged as mentioned below

Chapter 1 presents the background of slope stability analysis, current solutions, objective of the study and thesis organization.

Chapter 2 provides a detailed literature review as the works previously performed to mitigate slope failures, various solutions, current approach and a brief introduction on the potential materials that were used in the current study.

Chapter 3 describes the methodology and the specific conditions that were maintained during performing the test.

Chapter 4 presents the outcome of the study with discussions associated in each test.

Chapter 5 provides the summary, final conclusion and future recommendation of the current study.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Introduction

Slope stability problems have been encountered since the pre-historic times since mankind has disrupted the delicate balance of Mother Nature. With widespread rapid urbanization and increasing population, frequent cuts and fills caused irregular field contours that resulted a slope and consequently, stability issues.

#### 2.2 Background

When the analysis results indicate undesired low factors of safety, strengthening measures to prevent slope failures should be adopted. In general, the slope failure can be sub ordered into three leagues (Bromhead, 1992) .

- Strengths of subsoil – In case of steep slope, adequate strength of subsoil will be required to sustain the slope. Maximum failure occurs due to weak sub soil and sequent deterioration of the strength of the subsoil.

- Pore water pressure – Invasion or increase of pore pressure causes the effective stress of the soil to decrease and in case of heavy flooding or liquefaction, the effective stress becomes zero and cause the slope to slide down.

- Foreign paramountcies such as seismic forces, scouring, undercutting at the toe of the slope, man-made modifications for land use etc.

### 2.3 Available Slope Stabilization methods

As important as making a foundation and slabs of a structure to be level, equal, or might be more, importance should be focused on providing a safe and stable slope. To control settlements, uneven surface and pre-mature failing of surficials, care must be taken that the soil beneath is structurally sound. Till now, many methods have come in force to meet the challenge.

#### 2.3.1 Slope Stability by Ground Improvement

Improving the properties of soil by stabilization is considered as a means of fulfilling a major safety criterion in slope unsteadiness. Stabilization is usually performed to improve material properties of soil such as strength, stiffness, and permeability.

##### 2.3.1.1 Grouting

In case of liquefiable soils, colloidal silica grout has proven to be effective to stabilize ground disruptiveness (Gallagher et al., 2007). Colloidal silica is an aqueous dispersion of silica nano particles and it can be solidified by adjusting its chemical concentrations. This method is based on initially applying the solution to the edge of the proposed site and gradually targeting the desired location by natural groundwater flow. It increases the cementation between the individual grains and reduces the hydraulic conductivity responsible for generating liquefaction. Centrifuge modeling was applied to test the resistivity and deformation characteristics of susceptible soils. The treated soil proved to be restraint to shaking and thus provided a viable solution to liquefaction susceptibility.

##### 2.3.1.2 Chemical Stabilization

One of the methods of chemical stabilization is the mixing of soil with cement and the product is named as soil-cement (Croft , 1967). Soil cement can be defined as a mixture of soil and measured amounts of Portland cement and water and compacted to the required density. Soil can be mixed with cement and compacted in place using different mixing equipments. Soil-cement has been used as a base material as an adoption of improved measure in many projects,

such as slope protection of dams and embankments, pavement of highways, building pads, terminals for rail and truck, composting facilities, cheap base for streets, parking lots, channels and reservoir linings, mass soil-cement placement for dikes, foundation stabilization etc. The cement stabilization technique has been practiced almost for 100 years. Additives serve to amend the mechanical and the engineering properties of the soil. The new performance depends on the ability of the additives to react with the mixing soil. There are four main aspects of soil behavior—strength, permeability, volume stability, and durability—that may be improved using additives ( Estabragh et al., 2011). The choice of a particular additive is dependent on which of these factors is critical in any given situation that, in turn, depends on the fate of soil, surrounding environment and the service that is required to serve.

#### 2.3.1.3 Soil Bioengineering

Soil bioengineering is one of the recent applied technologies that have used the natural composts to treat soil instabilities (Hagen et al., 2007). This method involves use of plants and its parts as a construction material to provide environmental friendly solution to erosion, slope instability, stream bank stability and restoration of landfills. The mechanism of stabilization using soil bioengineering includes the enhancement of soil shear strength using vegetation–soil systems and resisting the soil particle movement. The progress made in the past few years with the contribution of the root system in slope stability is colossal. Various studies showed the beneficiary consequences of root density in preventing landslides (Gray, 1995) . By forming a binding network with the soil, roots impart significant anchorage which in turn increases the stability of slope (Ziemer, 1981) .

#### 2.3.1.4 Chemico pile

Chemical mixing of soil or, chemical grouting has been widely adopted to enhance the intrinsic properties of soil. Chemico-pile involves the use of chemically treated columns, made of chemically treated lime, being placed in-situ without mixing it with the soil. Hossain et al. (2007) investigated the performance of a treated embankment with chemico-pile using in-situ penetration



tests, as well as, numerical investigations using PLAXIS. Results monitored indicated a marked improvement in soil compressibility behavior and proved to be effective in shallow stabilization on embankments.

### 2.3.2 Concrete Slope Paving

Concrete slabs or mats are constructed on the face of the slope. There is some evidence that the concrete reduces moisture fluctuations and the effects of repeated wetting and can help improve long term stability. Thus, concrete paving may improve long term stability of slopes with highly plastic clays. Concrete Slope paving is probably primary beneficial in reducing some of the softening in high PI clays. Not likely to prevent moisture increases in the soil beneath riprap. This method can be detrimental if adequate drainage is not provided to allow water to escape from behind the concrete slab. Concrete slope paving can have detrimental effects; even the beneficial effects are not yet fully known.

### 2.3.3 Piles

Piles have been extensively used in many slope stability problems (Anagnostopoulos et al., 1991) . Some of the successful application of such technique has been reported by Ito and Matsui 1975, Sommer 1977 and Wang et al. 1979. The piles used in slope stabilization are usually subjected to lateral force by horizontal movements of the surrounding soil and hence they are considered as passive piles. Driven timber piles have been used to reinforce the failed slope in very soft clays in Sweeden. Cast in place reinforced concrete piles as large as 1.5 m diameter have also been used in Europe and United States to stabilize active landslides in stiff clays.. In an analysis of alterative measure, driven steel H-piles supplanted jet-grout columns for stabilization of an embankment slope (Thompson et al., 2007). For increasing the rail traffic capacity, an additional track adjacent to an existing main line was required to add. The initial slope stability analysis with a restricted slope of 2:1 (H:V) ranged a factor of safety from 1.2 to 1.5. The initial design included permanent soldier pile retaining walls in some portions and jet-grout “shear pins” in other locations to reinforce the slope. As the works was to be conducted on an active traffic

condition, the available space between the river and the existing rail line was not acceptable to safely operate jet grouting equipment. Later it was determined that driven piles could be safely installed without building temporary work areas and would prove to be better alternate of jet-grouted columns. The supposition was driven HP 310x79 (HP12x53) A572 Grade 50 steel pile sections spaced 0.9 m (3 ft) center to center along the crest of the slope, extending from the ground surface down to bedrock. For each stabilization option, the factors of safety for potential sliding surfaces were taken into account incorporating both double track and for the new set of tracks closest to the river, referred as single track. Comparison of computed factors of safety for the two stabilization options which is presented in Table 2.1 concluded that steel H-piles are equal to or greater than jet grout columns for all cases evaluated.

Table 2.1 : Comparison of Factor of Safety (Thompson et al., 2007)

<i>Cross-Section Station</i>	<i>Jet Grout Column</i>		<i>HP12x53 H-Pile</i>	
	<i>Double Track<sup>1</sup></i>	<i>Single Track<sup>2</sup></i>	<i>Double Track<sup>1</sup></i>	<i>Single Track<sup>2</sup></i>
4546+00	1.5	1.4	1.5	1.4
4598+00	1.4	1.3	1.5	1.4
4606+00	1.5	1.4	1.5	1.4
4619+00	1.5	1.3	1.5	1.3

<sup>1</sup>*Double track – potential sliding surfaces encompassing both sets of tracks*

<sup>2</sup>*Single track –potential sliding surfaces encompassing only the new set of tracks (closest to river)*

#### 2.3.4 Earth Retaining Walls

Earth retaining structure is generally a costly method but due to its flexibility in a constrained site it is commonly adopted for stabilizing the slopes. There are different types of earth retaining structure which include, gravity wall, cantilever wall, MSE wall etc. The principle of this method is to use a retaining structure to resist the downward forces of the soil mass.

Chen et al, 2005 reported a slope failure in Malayasia after a period of heavy rainfall. The slope was approximately 10 m high and 20 m wide and cosntructed on silty clay. Site investigation result revealed the depth of slipe surface was approximately 8 m (Figure 2.1). The

slope was stabilized with a reinforced type retaining structure at the toe of the slope to restrict any further movement of the downslope movement.

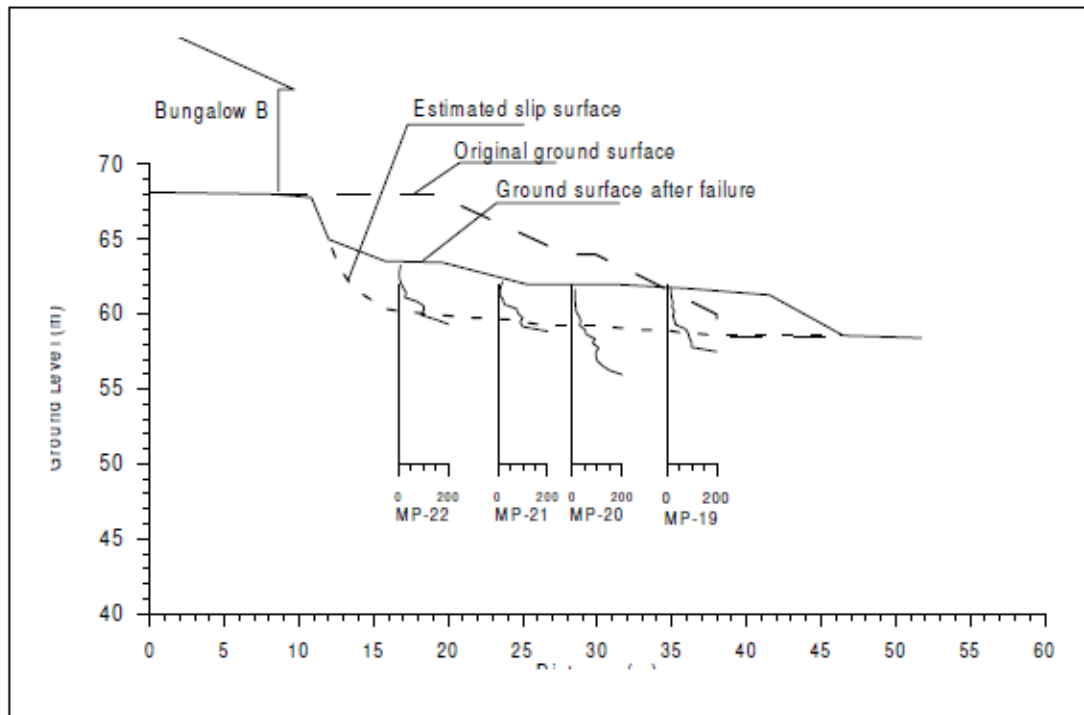


Figure 2.1: Site Investigation Results (Chen et al. 2005)

#### 2.3.5 Soil nails

Soil nailing has been proved to be a unique and cost effective technique in the stabilization of slopes and earth retaining structures. The fundamental concept of soil nailing is to reinforce the soil with closely spaced to create a harmonious gravity structure and thereby increase the overall shear strength of the in situ soil to restrain the soil instabilities. The fundamental design concept is to transfer the resisting tensile forces generated in the inclusions into the slope by utilizing the friction mobilized at the nail/soil interfaces.

Chen et al 2005 reported a successful implementation of soil nailing for a failed slope in Malaysia. The riverbank slope of a water treatment plant had been continuously eroded and consequently caused shriveling slips. Tension cracks were found on the surface upon investigation. The subsoil showed to be of medium stiff to stiff silty and clayey residual soil. As the

site is located in a remote area, the access to site was an important issue when selecting a suitable remedial measure. Initially, retaining wall was proposed for the abatement but temporary excavation during construction may cause further damage to the plant. With all the issues in mind, it was decided to use soil nails to stabilize the unstable slope. The advantages of using soil nails for this case was that accelerated installation can be performed and the equipments required were light and had no problem in transportation and operations. As the slope surface was covered by a layer of shotcrete to prevent further erosion, horizontal drains was installed for inhibiting the buildup of excess pore pressure behind the shotcrete facing. Riprap was placed at the toe of the slope to arrest undermining. Figure 2.2 shows the stabilized slope after installation of soil nail.



Figure 2.2: Site Condition after Remedial Works (Chen et al. 2005)

The above existing methods to stabilize slope has some advantage and disadvantage over the filled conditions. Most of the slope failures in Texas include shallow slides which is limited up to top few feet of soil. The general practice for stabilizing such slopes by TxDOT is to construct retaining walls or soil nail which became costly method to address such shallow slides. Therefore an alternative approach to stabilize such slopes has been proposed using Recycled Plastic Pins, The scope for using Wood and Bamboo as a reinforcing member is also discussed in the following section.

## 2.4 Alternate Materials for treating Slope Instability

### 2.4.1 Plastic Pin

A new scheme for stabilization of slope using plastic pin has recently been developed. Plastic pins are fabricated from recycled plastics and other waste materials (polymers, sawdust, fly ash), to provide positive reinforcement of a soil mass. Typically, recycled plastic pins is composed of the following resins (McLaren, 1995):

- High Density Polyethylene (HDPE)- 55 percent to 70 percent
- Low Density Polyethylene (LDPE)- 5 percent to 10 percent
- Polystyrene (PS)- 2 percent to 10 percent
- Polypropylene (PP)- 2 percent to 7 percent
- Polyethylene-terephthalate (PET)- 1 percent to 5 percent, and
- Varying amounts of additives (sawdust, flyash)- 0 percent to 5 percent

The mechanical properties and performance of plastic pins can vary based on the material composition and manufacturing process. A brief overview of different types of recycled plastic lumbars is presented in Table 2.2.

Table 2.2: Different types of RPPs

<b>Types</b>	<b>Composition</b>	<b>Advantages</b>	<b>Disadvantages</b>
High Density Polyethylene (HDPE) RPP	Consists of 95 percent High Density polyethylene	1. Excellent performance and resistance to decay. 2. Less maintenance cost	1. Higher initial Cost. 2. Lower stiffness than wood.
Wood-Filled RPP	Consists of 50 percent sawdust with 50 percent polyethylene	1. Less expensive. 2. Greater surface roughness 3. More paint ability.	1. Behaves more like wood and proper maintenance is required to prevent stains. 2. Degradation and decay problems.
Fiber-Reinforced RPP	Consists of plastic mixed with chopped or continuous strands of glass fiber	1. More strength than its counterparts. 2. Good structural applications 3. More paint ability.	1. Highest initial cost. 2. Less flexibility

The application of recycled plastic pins in stabilizing slopes is similar to stabilization of slopes with soil nails or micropiles, but this method is relatively cheaper. This method is applicable for failures relatively in shallow depth.

Plastic pins driven into the slope face crossing the slip surface provides an additional resistance force along the slip plane thus increasing the factor of safety. The definition of factor of safety is the ratio of resisting moment to the driving moment which is presented in Eq. 2.1. Plastic lumber installed at the slope offers an additional resisting moment which is presented in Eq. 2.2. A schematic diagram of the stabilizing force from pins is presented in Figure 2.3.

$$FS = \frac{M_R}{M_D} \quad (2.1)$$

$$FS = \frac{M_R + \Delta M_R}{M_D} \quad (2.2)$$

Where,  $M_R$  = Resisting Moment along Slip Surface

$M_D$  = Driving Moment along Slip Surface

$\Delta M_R$  = Additional Resisting Moment from Plastic Pin

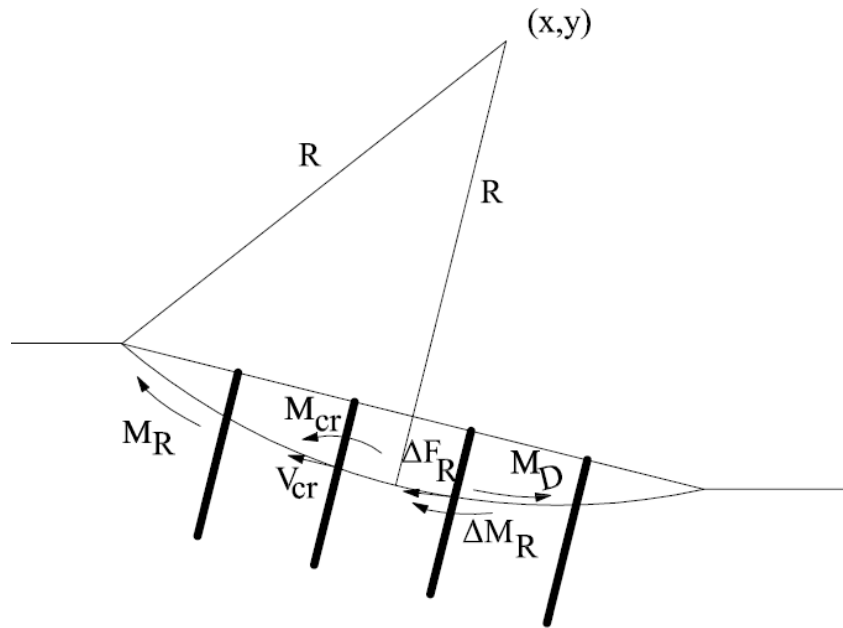


Figure 2.3: Resistance Force acting on Soil from Plastic Pins (Loehr et al., 2003)

The design methodology of slope stabilization using recycled plastic pins involves finding the limit lateral resistance of individual reinforcing members. The procedure considers the following limit states (Loehr and Bowders 2003):

- Failure of soil around or between reinforcing members – referred to as the limit soil resistance,
- Structural failure of reinforcing members in shear or bending due to load application from the soil mass – referred to as the limit member resistance, and
- Failure of soil due to insufficient anchorage length – referred to as the limit anchorage resistance.

#### Limit Soil Resistance

The proposed design method employs the model for ultimate soil pressure originally proposed by Ito and Matsui (1975). The ultimate soil pressure of the model increases linearly with



depth. The design method assumes that the ultimate soil pressure is mobilized along the entire length of pile subject to lateral soil movement, and the limit soil pressure is integrated from the ground surface to potential sliding depths. The integration, with units of force, is called the limit soil resistance,  $F_R$ . The limit soil resistance increases as the depth to the sliding surface increases, because the length over which the ultimate soil pressure is integrated increases. The integration of ultimate soil pressure and the limit soil resistance curve is shown in Figure 2.4 (a) and (b), respectively.

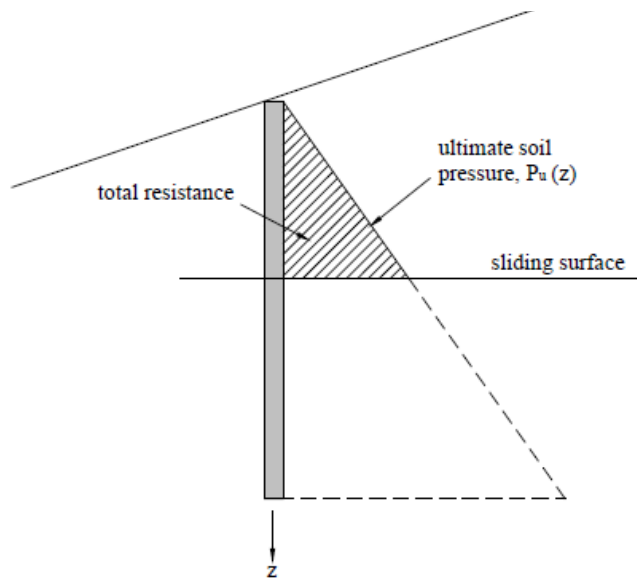
#### Limit Anchorage Resistance

Incorporation of limit anchorage resistance ensures that pile elements do not induce passive failure of the soil below the sliding surface. For potential sliding depths, the limit soil pressure is integrated from the depth of the sliding surface to the bottom of the pile. The limit anchorage resistance decreases as the depth to the sliding surface increases (for a given pile length), because the length over which the ultimate soil pressure is integrated decreases. Piles that extend only to the failure surface, for example, clearly offer no resistance to slope movement. The integration of ultimate soil pressure and the limit anchorage resistance curve is shown in Figure 2.5 (a) and (b), respectively.

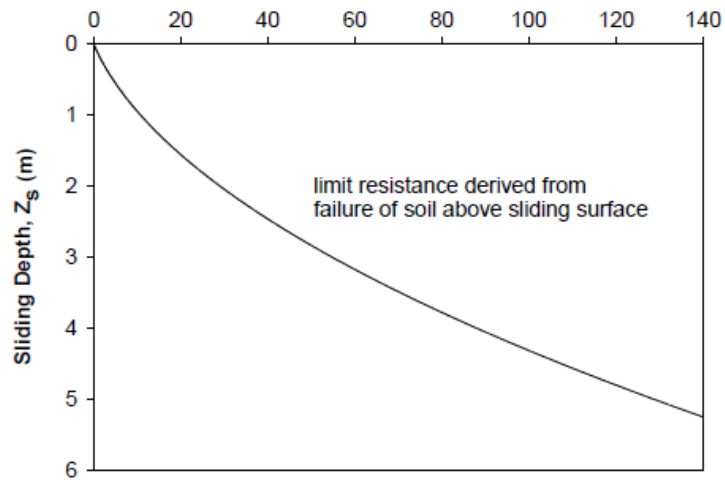
#### Limit Member Resistance

The development of a limit member resistance curve to account for the structural capacity of pile elements uses the ultimate soil pressure and a reduction factor, where the application of the ultimate soil pressure may lead to bending moments or shear forces that exceed the capacity of the reinforcing member (Loehr and Bowders 2003). The reduction factor,  $\alpha$ , is the factor by which the ultimate soil pressure is applied to the pile element that just causes the pile to fail in either bending or shear (see Figure 2.6). The maximum moment (or maximum shear) developed by the factored soil pressure distribution equals the moment capacity (or shear capacity) of the pile section, observing that the limit member resistance represents the maximum load that is

carried by the pile. The limit member resistance curve is developed similarly to the limit soil resistance curve, where the former uses the factored soil pressure distribution along the pile and the latter uses the unfactored soil pressure distribution along the pile. The factored ultimate soil pressure distribution is integrated from the ground surface to the potential sliding depth, such that the length over which the factored soil pressure is integrated increases with sliding depth. The limit member resistance decreases with sliding depth, however, because  $\alpha$  decreases with sliding depth. The reduction factor, which is inversely proportional to the maximum moment developed in the pile, decreases with sliding depth; because the moment arm of an equivalent loading condition increases. As the moment arm increases, the calculated maximum moment increases. For this reason, at intermediate sliding depths where  $\alpha$  is less than 1.0, member resistance controls the reinforcement capacity. The establishment of the reduction factor and use of the factor to modify the soil pressure distribution is illustrated in Figure 2.6. The limit member resistance curve is presented in Figure 2.7.

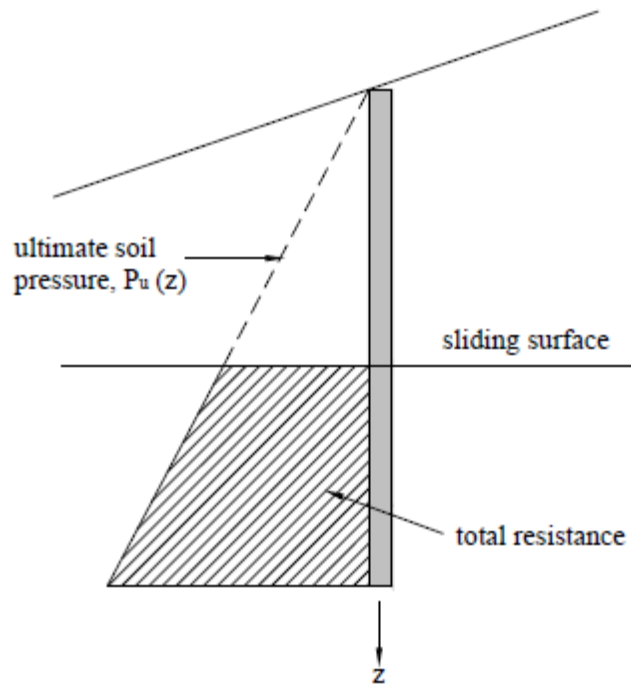


(a) Integration of Limiting Soil Pressure

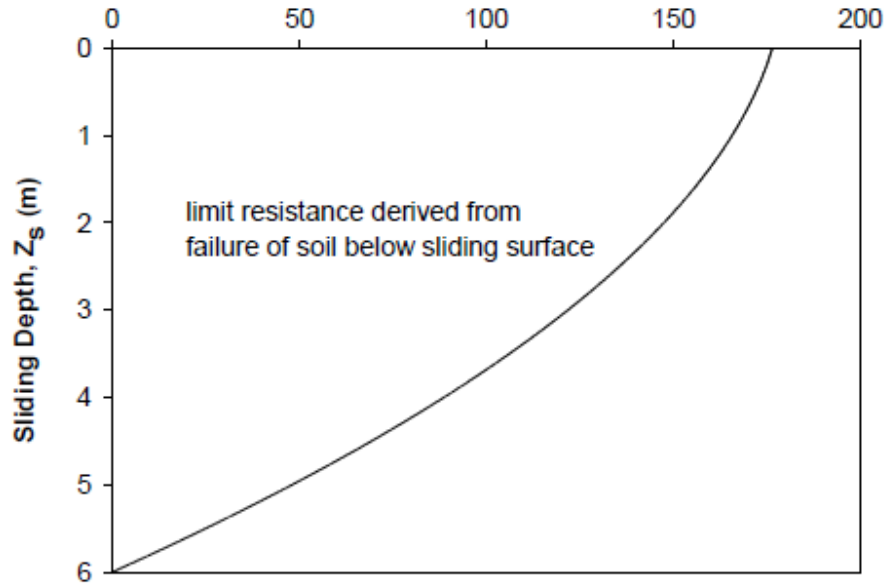


(b) Limit Soil Resistance Curve

Figure 2.4: Limit Soil Resistance (Loehr and Bowders 2003)

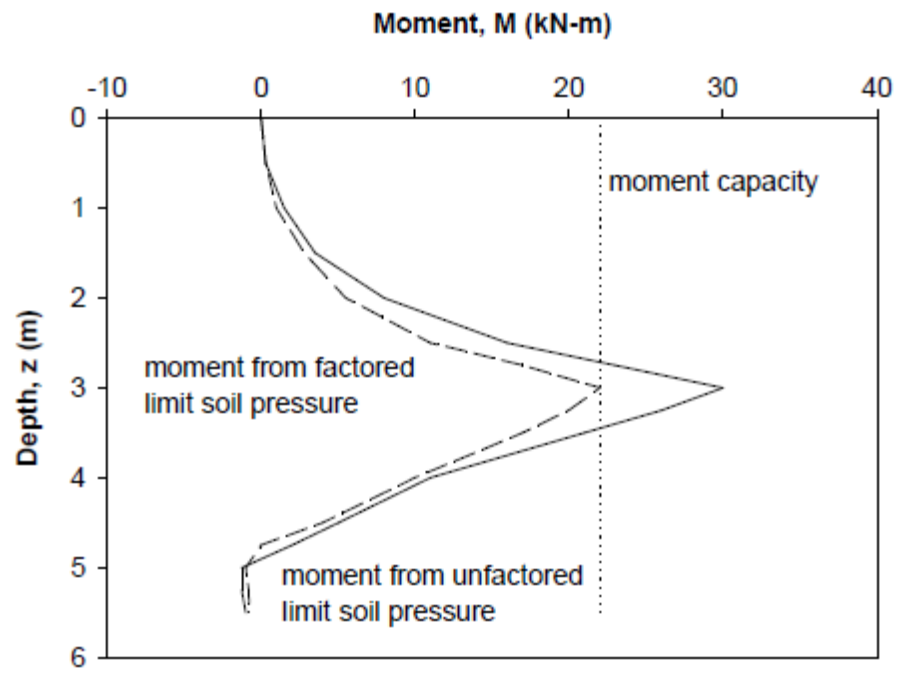


(a) Integration for Limiting Anchorage Resistance

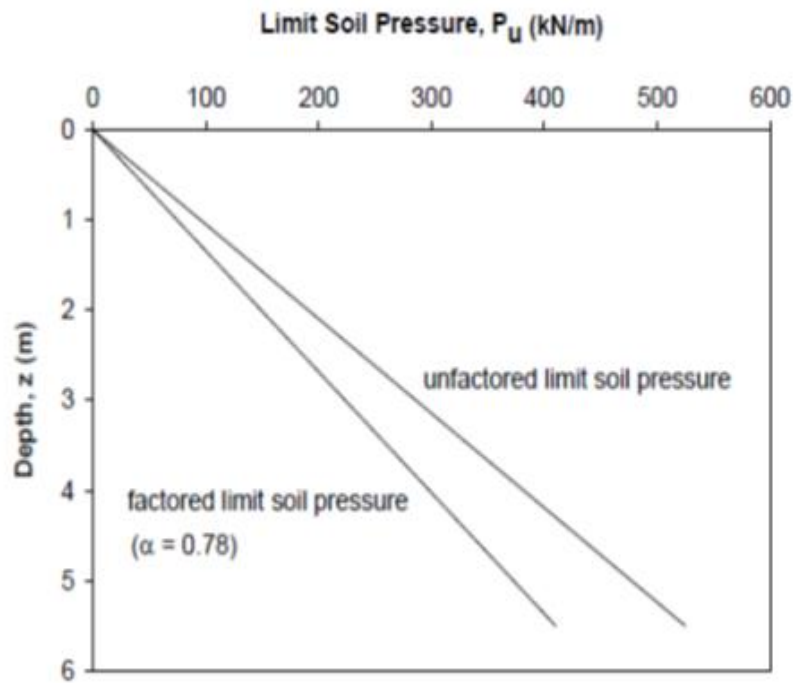


(b) Limit Anchorage Resistance Curve

Figure 2.5: Limit Anchorage Resistance (Loehr and Bowders 2003)



(a)



(b)

Figure 2.6: Factored Pressure Distributions (Loehr and Bowders 2003)

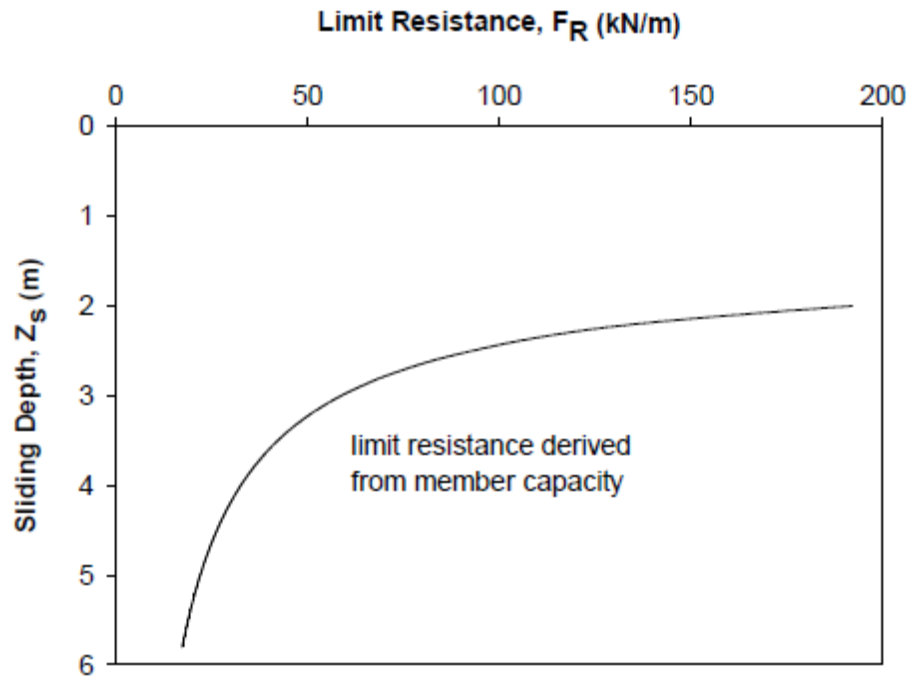
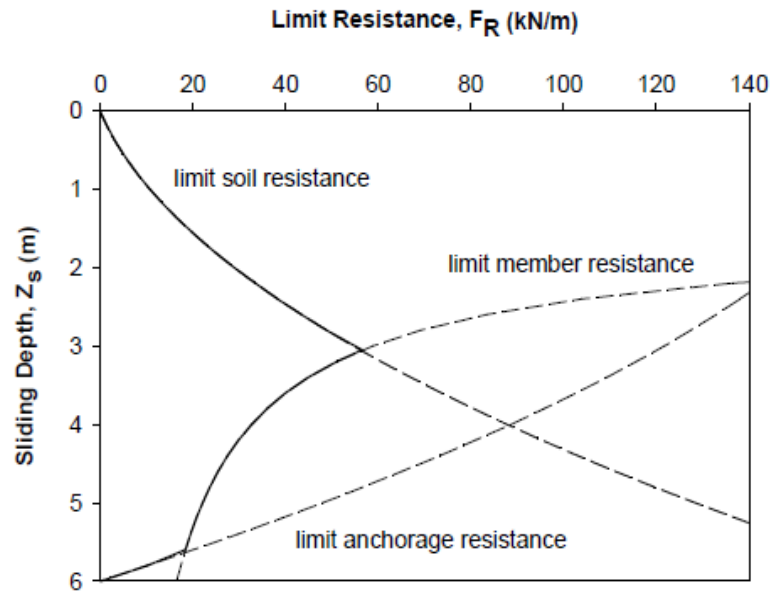


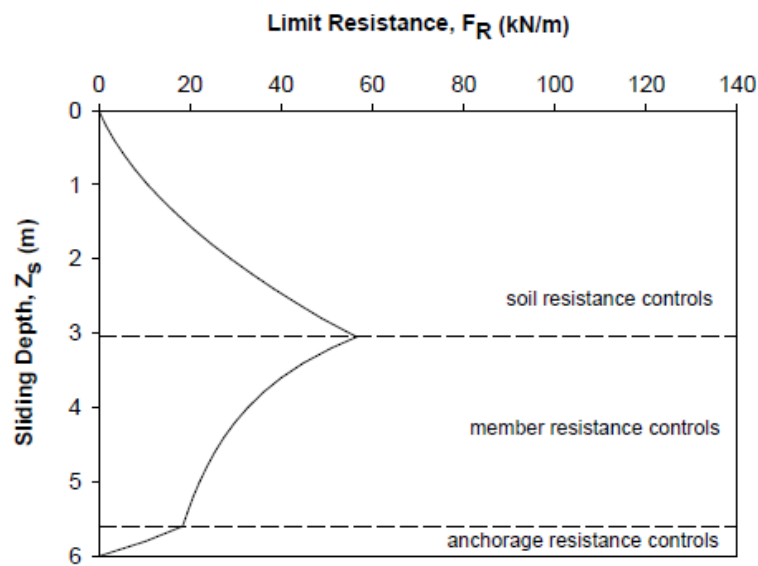
Figure 2.7: Limit Member Resistance Curve (Loehr and Bowders 2003)

#### Composite Limit Resistance Curve

For each limit state (e.g. soil resistance, anchorage resistance, and member resistance), a factored or unfactored limit soil pressure is determined and appropriately integrated to find the respective limit resistance for a given sliding depth. The limit resistance of the system is the least of the three limit states considered. Figure 2.8 shows typical distributions of limit resistance and a composite limit lateral resistance



(a) Determination of Reduction Factor,  $\alpha$



(b) Factored Limit Soil Pressure

Figure 2.8: Limit Resistance Distribution for Recycled Plastic Lumbers (Loehr 2003)

#### 2.4.1.1 Properties of Plastic Pins

Engineering properties of reinforcing plastic pins has become an attention as to analyze the strength and creep effects (Chen et al., 2007). It has become vitally important because of the potential for structural failure of the pins due to the moving soil loads and the resisting stress imparted by the installed members. A detailed investigation on the properties of plastic pin was performed by (Loehr and Bowders, 2007) which included uni-axial compression, four-point flexure, compressive creep, and flexural creep tests. From the laboratory investigation it was found that compressive strengths of plastic pin ranged from 11 to 20 Mpa and compressive moduli ranged from 580 to 1,280 MPa at 1% strain The flexural strengths of plastic pin ranged from 9 to 25 MPa and flexural moduli ranged from 620 to 1675 MPa at 1% strain. Manufacturing variation was considered in the testing taking the compression and extrusion mold.

Table 2.3: Summary Results of RPP Tested (Loehr and Bowders, 2007)

Specimen batch	Principal constituent	Manufacturing process	Unit weight (kN/m <sup>3</sup> )	Uniaxial compression strength <sup>a</sup> (MPa)	Secant compression modulus, $E_{1\%}$ (MPa)	Flexural strength <sup>b</sup> (MPa)	Secant flexural modulus, $E_{1\%}$ (MPa)
A1	LDPE	Compression	10	19	924	11	710
A2	LDPE	Compression	10	20	1,269	— <sup>c</sup>	—
A3	LDPE	Compression	10	19	1,131	—	—
A4	LDPE	Compression	10	18	1,282	18	1,469
A5	LDPE	Extruded	9	11	579	11	676
A6	HDPE	Extruded	10	11	641	9	655
A10	HDPE	Extruded	11	15	786	11	848
B7	HDPE	Extruded	8	14	600	10	621
B8	HDPE+fiberglass	Extruded	8	17	952	25	1675
C9	HDPE	Extruded	11	16	600	12	738

Note: Conversion: 1 kN/m<sup>3</sup>=6.361 pcF; 1 MPa=145 psi.

<sup>a</sup>Use original cross-sectional area ( $A_0$ ) to calculate stress.

<sup>b</sup>All results based on stress at 2% center strain or center strain at rupture of less than 2%.

<sup>c</sup>Data not available.



#### 2.4.2 Wood

Wood is a hard, fibrous tissue often cut and dried especially for use as building material and fuel (Appalachian Hardwood Manufacturers, 1994). It is a raw material that can satisfy almost every requirement or existence and the world's most important sources of textile fibers. As an engineering material, wood yields an astonishing variety of furnished woods, plastic and wood fiber products that can meet any engineering specification. Wood has a typical flexural modulus of 1.6 ksi and compressive modulus of 1.2 ksi . Wood can be a potenital material for reinforcing slope based on the same principle outlined in the previous section.



Figure 2.9: Wood Lumbers (Coferadams, 2010)

The mechanical properties and performance of wood lumbers can vary based on the material composition and manufacturing process. A brief overview of different types of recycled plastic lumbers is presented in Table 2.4.

Table 2.4: Different types of Wood

Types	Composition	Advantages	Disadvantages
Plywood	Manufactured from sheets of cross-laminated veneer and bonded under heat and pressure with durable, moisture-	1. High uniform strength. 2. Non-splitting qualities. 3. Economical.	1. More susceptible to weathering effects. 2. If used incorrectly, it will rapidly fail.
Glue Laminated Timber	Composed of several layers of dimensional timber glued together with moisture-resistant adhesives	1. Very good for structural applications. 2. Good strength to weight ratio. 3. Corrosion resistant.	1. Additional cost for finishing. 2. If used incorrectly, it will rapidly fail.
Laminated veneer lumber	Manufactured by bonding thin wood veneers together in a large billet	1. Excellent for beam, joist and column applications. 2. Stronger, more uniform product.	1. More costly to produce.
Parallel strand lumber	Made of long veneer strands laid in parallel formation and bonded together with an adhesive to form the finished structural	1. Resistant to seasoning stress. 2. High load carrying ability.	1. More costly and energy to manufacture.

#### 2.4.2.1 Properties of Wood

The general term “strength” for wood is related to a number of specific strength or mechanical properties due to varying inherent features. Before being suitably applied in regards to strength, proper consideration must be focused to the desired mechanical properties for the proposed use. Table 2.5 shows results for different types of wood that are most commercially applied in building applications in USA.

Table 2.5: Properties of some commercially important woods grown in USA (Hiziroglu, 2002)

Species	Modulus of Elasticity in static bending (ksi)	Axial Compressive strength (ksi)	Shear strength parallel to the grain (ksi)
Douglas Fir	1950	3.7	0.9
Sitka spruce	1570	5.6	1.2
White Pine	1240	4.8	0.9
Eastern reducedar	880	3.52	1.01
Red pine	1630	6.1	1.2
Cottonwood	1100	4.02	0.79
Red oak	2200	6.8	2.02
Cedar	1500	3.1	1.4
Hemlock	1200	5.4	1.1
Tamarack	1240	3.4	0.8
Sassafras	910	2.7	0.95

In a research, a detailed analysis of the wood specie, spruce, was performed to judge its applicability on wooden frame buildings (Isopescu et al., 2012). The analysis was performed with three-point bending test on ten samples of spruce wood. Each samples were 20mm. x 20mm. in cross-section with 380 mm. span and subjected to a loading rate of 0.85 MPa/s. The moisture content within the samples was also considered in the test. Table 2.6 shows the detail test results

of the study. It is observed from the results that even with the same specimen, different samples showed different strength values. The variation might be due to natural anisotropy and different moisture contents within the specimen.

Table 2.6: Three-point flexure results of spruce wood (Isopescu et al., 2012)

Specimen No.	Moisture content (%)	$P_{max.}$ (N)	$\delta_{max.}$ (mm.)	$\sigma_{max.}$ (MPa)	E (MPa)
1.	7.4	1730	7.5	74.54	7120
2.	7.4	2090	6.5	83.84	8200
3.	8.0	1830	5.8	74.11	7130
4.	7.0	2030	6.1	80.94	8850
5.	7.2	2120	5.9	88.74	9200
6.	7.6	2340	7.3	95.91	10300
7.	7.2	2000	6.3	85.89	8840
8.	7.0	2430	7.3	93.26	9400
9.	7.4	1880	5.9	76.93	7800
10.	7.8	1960	6.4	80.76	7510

The mechanical properties of wood also vary when they are exposed to detrimental environmental effects (Winady, 1994). For clear wood, engineering property increases as wood dries below 10 to 15% moisture content. For lumber, studies reflected that mechanical property values hit maximum at 10 to 15% moisture content. Also strength and stiffness decrease when wood is heated and increase when cooled. If wood is exposed to elevated temperatures for a certain time, strength is permanently reduced due to inherent degradations. The magnitude of these permanent effects depends on moisture content, temperature, period of exposure and heating medium. It was also found from the same study that, wood should not be exposed to temperatures above 65<sup>0</sup> C.

### 2.4.3 Bamboo

Bamboo is one of the fastest growing plant in the world and readily available in developing countries like: South Asia. The hard woody stems of bamboo plants mostly used as a construction material. The hollow tube shape gives a strength factor of 1.9 times more than an equivalent solid wood beam (Bamboo Technologies). Typical flexural modulus is 6.6 ksi and typical compressive modulus is 4.6 ksi (Trujillo, 2008).



Figure 2.10: Bamboo ( Bamboo Garden, 2010)

#### Advantages:

- Sustainable and strong.
- Cheaper compared to its counterparts.
- Good strength in bending and compression.
- Flexible

#### Disadvantages:

- Very weak in tension perpendicular to its axis.
- Splits a lot.

#### 2.4.3.1 Properties of Bamboo

Bamboo has tremendous economic potential and serves as one of the strongest building materials. In recent times, bamboo as reinforcement has been studied regarding its application as a building material (Sabbir et al., 2011). The study was conducted with two bamboo samples from the same species and four-point flexure test was performed. It was observed from the results that one sample showed a peak strength of 150 MPa and the other one showed a peak strength of 120 MPa, as observed from Figure 2.11.

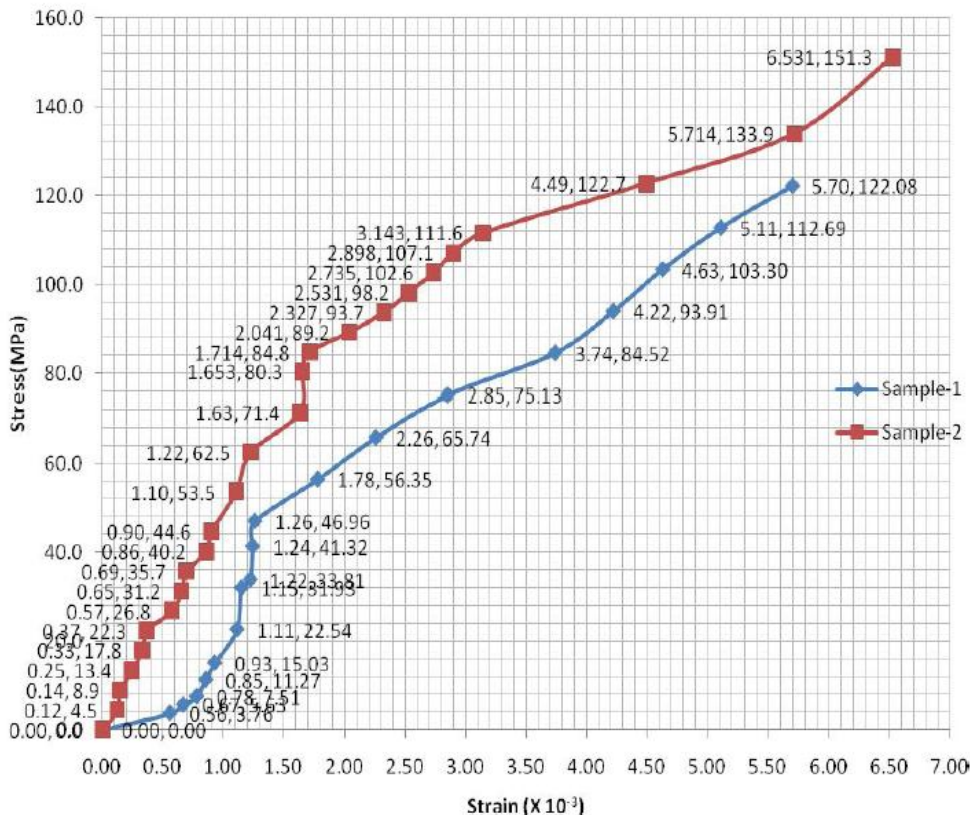


Figure 2.11: Stress –strain behavior of bamboo (Sabbir et al., 2011)

It was observed from the results engineering properties of bamboo composites vary due to significant variability in mechanical constituents even within the same species. Overall, bamboo composites are comparable to those of wood and other natural products. Considering the fact

that bamboo is a rapid growing plant available in abundance, it can find various structural applications. Another study was performed considering different types of bamboo that are commonly used in developing countries for engineering applications (Naik, 2001). The analysis was conducted considering the axial and flexural behavior of different types of bamboos. Table 2.7 shows the test results that were obtained from their experiment.

Table 2.7: Mechanical properties of different types of Bamboo (Naik, 2001)

Bamboo specie	Average dia (cm.)	Moisture content (%)	Compressive strength (MPa)	Shear strength (MPa)	Bending strength (MPa)	Bending Modulus of Elasticity (MPa)
Bambusa tulda	10	8.62	79	9.9	194	18611
B. Balcooa	20	8.46	69	11.9	151	13603
B.bambos (B.arundinaceae)	25	9.15	61	9.9	143	14116
B.nutans	15	8.94	75	10.5	216	20890
Dendrocalamus giganteus	26	8.02	70	10.6	193	16373
D. hamiltonii	16	8.16	70	6.7	89	9629
Gigantichloa macrostachya	15	8.08	71	9.6	174	14226
Melocanna Bambosoides	14	8.28	81	7.1	137	16425
Phyllostachys Bambusoides	10	7.98	63	8.7	127	10982

The natural durability of bamboo is very low and depends on application type, specie and environmental condition. With covering conditions, untreated bamboo may last 4-7 years (Kumar et al., 1994). Systematic data on natural durability when there is ground contact and exposed conditions are very limited.



## CHAPTER 3

### METHODOLOGY

#### 3.1 Introduction

The objective of this study was to determine the flexural strength and compressive strength of structural wood, bamboo and Recycled Plastic Pin and perform a comparative study to determine as which of them was more structurally feasible to encounter slope stability problems. To determine the flexural strength, 3-point bending test was performed, in accordance with ASTM D790, and uni-axial compressive strength test was performed to determine the compressive strength, in accordance with ASTM D6108. An experimental program was developed to study the engineering characteristics of RPP, wood lumber and bamboo as mentioned in Table 3.1

Table 3.1: Experimental Program

Test Name	Loading Rate	No of Tests		
		RPP	Wood	Bamboo
Three Point Bending Test	0.5 kips/min.	3	3	3
	2.7 kips/min.	3	3	3
	4.9 kips/min	3	3	3
<b>Total: 68" x 3.5"x 3.5" sample</b>		<b>9</b>	<b>9</b>	<b>9</b>
Uniaxial compression test	2.5 kips/min.	3	3	3
	3.1 kips/min.	3	3	3
	3.75 kips/min	3	3	3
<b>Total: 7" long 3.5"x 3.5" sample</b>		<b>9</b>	<b>9</b>	<b>9</b>
<b>Environmental Effects in Compression</b>				
pH –5.5, Acidic solution	2.5 kips/min.	3	3	3
	3.1 kips/min.	3	3	3
	3.75 kips/min	3	3	3
pH – 7.0, Neutral solution	2.5 kips/min.	3	3	3
	3.1 kips/min.	3	3	3
	3.75 kips/min	3	3	3
pH – 8.5, Alkaline solution	2.5 kips/min.	3	3	3
	3.1 kips/min.	3	3	3
	3.75 kips/min	3	3	3
<b>Total: 7" long 3.5"x 3.5" sample</b>		<b>27</b>	<b>27</b>	<b>27</b>

### 3.2 Sample collection

For Recycled Plastic Pins, the samples were collected that are currently being used in slope stabilization in US 287 and Loop 12. The length x width x height being 10' x 3.5" x 3.5". The wood that was used in the research is Cedar, most commonly used in structural applications for timber-built houses (Cedar wood applications, 2012). The length x width x height was 8' x 3.5" x 3.5", as typically available. For bamboo poles, fully ringed hollow samples, with the average diameter being 3.5 inches and length was 12 feet was considered.

### 3.3 Sample preparation

#### 3.3.1 Bending

Flexural strength is a measure of the material resistance to deformation under applied loads. When load is applied, it experiences a range of stresses across the depth of the specimen, as presented in the Figures 3.1, 3.2 and 3.3.

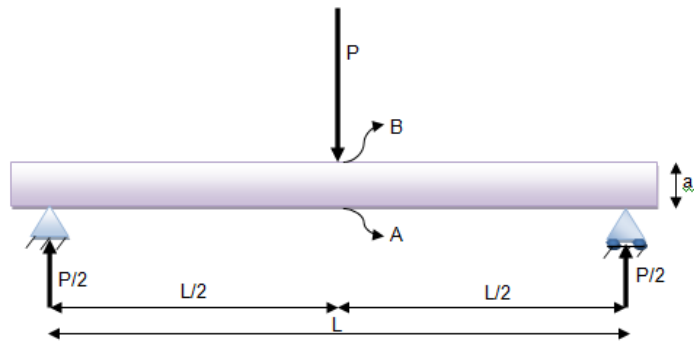


Figure 3.1: Schematic Diagram of a Three Point Bending Test

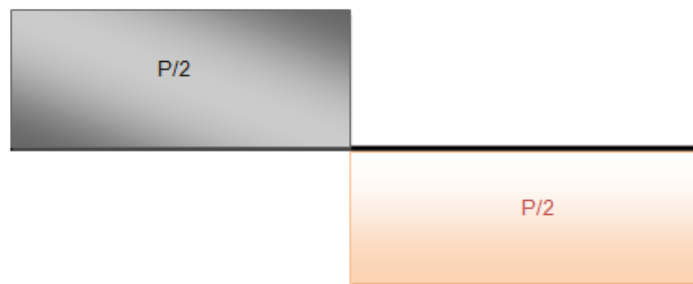


Figure 3.2: Shear Force Diagram for the Three Point Bending Test

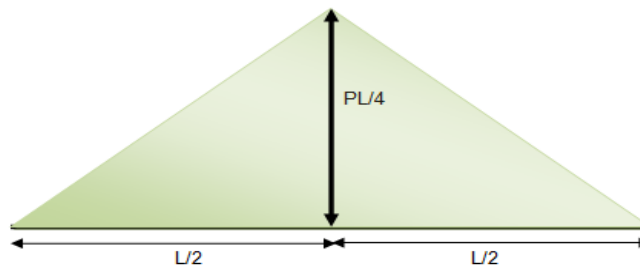


Figure 3.3: Bending Moment Diagram for the Three Point Bending test

For a 3-point Loading, the stress is calculated as shown below

$$\sigma = \frac{3 * P * L}{2 * b * a^2} \quad (3.1)$$

Where,

P = maximum load at fracture

L = loaded span

b = width of the beam

a = depth of the beam

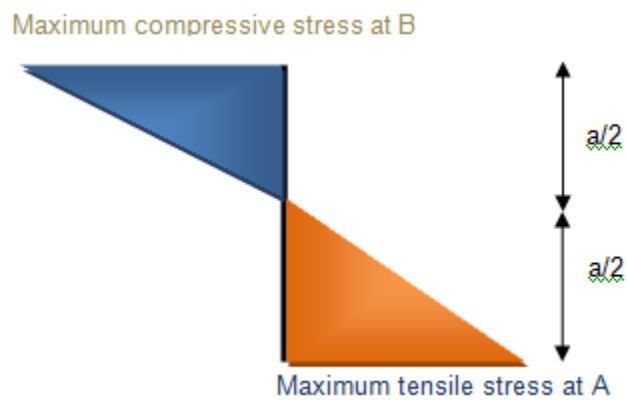


Figure 3.4: Stress Diagram across A to B

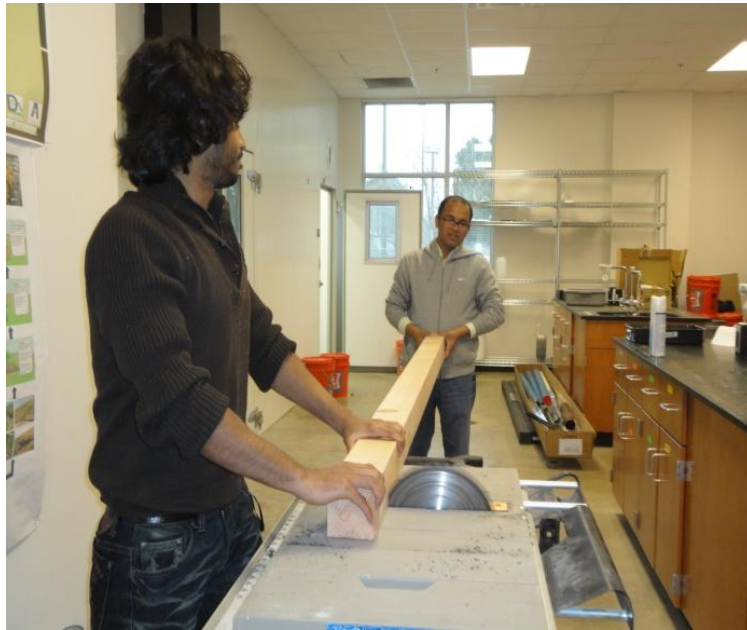


Figure 3.5: Sample Preparation for flexure test



Figure 3.6: Prepared Bamboo sample for flexure test

### 3.3.2 Compression

Compressive strength is the ability of the material resistance to axial deformation under axial loads.

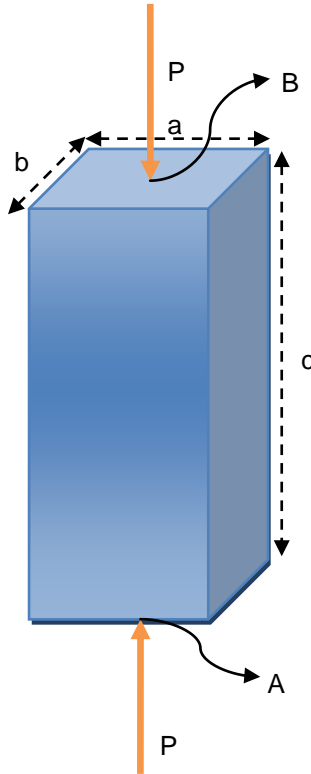


Figure 3.7: Uniaxial Compression Test

Compressive stress is calculated by,

$$\sigma = P/A$$

Where,

P = axial load to fracture

A = cross-sectional area perpendicular to applied load

Considering uniform distribution of stress throughout the depth of the specimen, the stress distribution is shown below

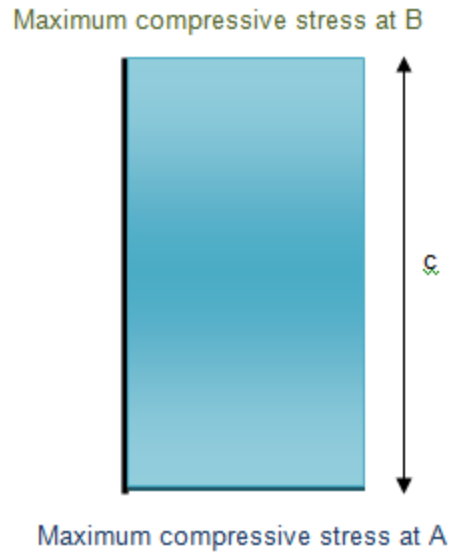


Figure 3.8: Stress Distribution across A to B

For compression, the samples were prepared as the specimen height = 2 x minimum width, in accordance with the ASTM standards. As our minimum width for all specimens was 3.5 inches, the height of each sample was 7 inches in height. A total of nine samples were prepared for three loading conditions with three being for each loading rate. For the environmental degradation test, three environment conditions were selected, which will be described in the conceding sections, and as such, twenty-seven samples for each environment conditions and similar loading conditions were prepared.



Figure 3.9: Prepared RPP sample for compression test



Figure 3.10: Prepared Bamboo samples for compression test



### 3.4 Test methodology

The main concept of both the states is to load the specimen till yielding occurs. The resulting values of stress and strain were plotted and maximum yield stress was determined from the graph.

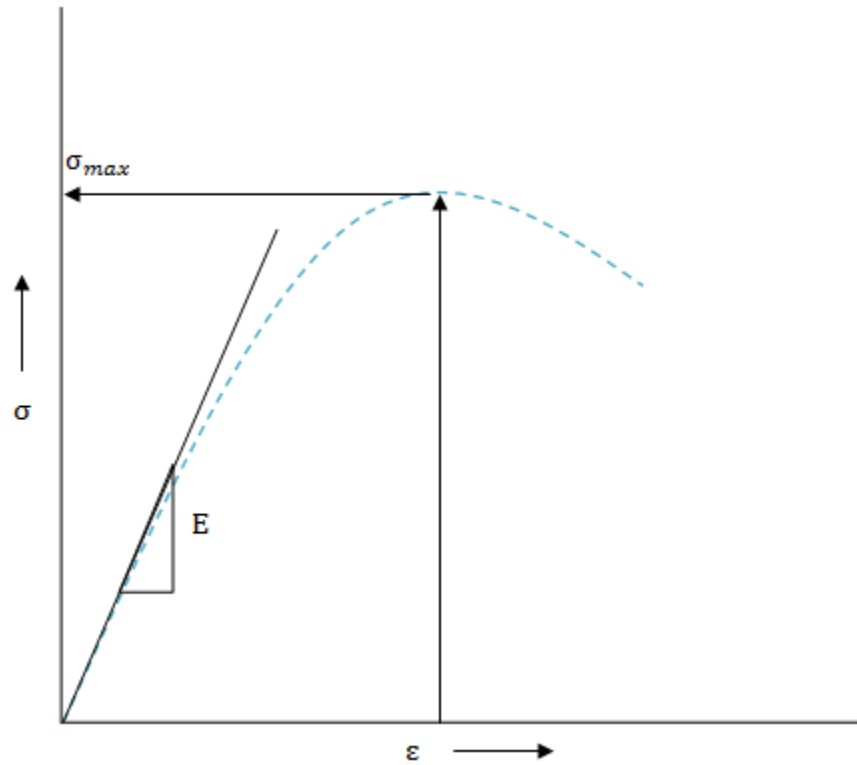


Figure 3.11: Typical Stress-strain response

Currently, Recycled Plastic Pins in Loop 12 Dallas and in US 287 was installed as a measuring step to relieve the slope stability problems encountered there. The current study was performed under the conditions similar to that of the plastic lumbers, for wood and bamboo and examines the effect whether they will sustain in same conditions. The ASTM standards suggest controlled strain rates to perform both the tests. Since the lab is equipped with controlled loading rates, the strain rates were transferred into loading rates.

In the current study, the reference material was Recycled Plastic Pin. Therefore, the applied loading rates corresponding to the strain rates for the plastic lumbers for all three specimen types was considered (Loehr and Bowders, 2007) . The Table 3.4.1 shows the summarized values for my experiment.

Table 3.2: Loading rates in compression with the number of samples

Loading Rate (kips/min.)	Recycled Plastic Pin	Bamboo	Wood	Total
2.5	3	3	3	9
3.5	3	3	3	9
3.75	3	3	3	9

To evaluate the environment effects, Texas is primarily composed of black and red clay. The black clay being basic in nature consists of a pH of 7 to 8.5 (Texas High Plains Region, 2008) and the red clay is acidic in nature being a pH value of 5.5 (Kellenberg, 2000) . The environmental degradation effects in the current study was categorized into three types, keeping the loading rates fixed as before-mentioned to simulate the effects on the strength.

Table 3.3: Loading rates in compression with the environment conditions

pH	Loading		Recycled Plastic Pin	Bamboo	Wood	Total
	Rate (kips/min.)					
pH = 5.5, Acidic	2.5	3	3	3	9	
	3.5	3	3	3		
	3.75	3	3	3		
pH = 7.0, Neutral	2.5	3	3	3	9	
	3.5	3	3	3		
	3.75	3	3	3		
pH = 8.5, Alkaline	2.5	3	3	3	9	
	3.5	3	3	3		
	3.75	3	3	3		

For preparing samples for environmental degradations in three different conditions, the sample was submerged in three large tubs filled with water, basic and acidic solutions respectively.



Figure 3.12: Tubs that were used for sample submergence in environment conditions

The samples were submerged in each of the solutions for two months. For acidic and basic solutions, the samples were kept, with sealed covers, inside the lab in room temperature. There

was a possibility of the pH of both the solutions to change. As such, a weekly observation on the samples was carried to check the pH of the solutions and measures were taken accordingly to maintain the desired level.



Figure 3.13: Initial filling of the samples from each specimen



Figure 3.14: Samples sealed in Alkaline condition

For the neutral solution, the samples were kept open in a hot room, with no covers, to simulate the effect of heat with moisture on the samples.



Figure 3.15: Samples placed in the hot room with the top uncovered

In the current study, the reference material was Recycled Plastic Pin. Therefore, the applied loading rates corresponding to the strain rates for the plastic lumbers for all three specimen types was considered, according to the ASTM standards. The Table 3.4 shows the summarized values for the experiment

Table 3.4: Loading rates in flexure with the number of samples

Loading Rate (kips/min.)	Recycled Plastic Pin	Bamboo	Wood	Total
0.5	3	3	3	9
2.7	3	3	3	9
4.9	3	3	3	9

Both the tests were performed in the UTM machine.

## CHAPTER 4

### RESULTS AND DISCUSSIONS

#### 4.1 Introduction

The laboratory tests were conducted to perform a comparative study between wood, bamboo and plastic lumber. The test results obtained from the three-point bending tests and uni-axial compression tests are discussed in the following subsequent sections.

#### 4.2 Three-Point Bending Test

The three point bending tests were conducted at three strain rates: 0.01 in/in/min, 0.06 in/in/min and 0.1 in/in/min respectively. The tests were conducted at the testing facility where the loading rate can be controlled instead of the strain rate. Therefore the equivalent loading rate of was calculated and the tests were conducted. The equivalent loading rate for the test were 0.5 kips/min., 2.7 kips/min. and 4.9 kips/min respectively. Each test was performed until the specimen fails to accommodate the loading rates.

##### 4.2.1 Recycled Plastic Pin

The length of each sample was 68 inch during the test. The total length of the specimen includes 56 inches support length was 56 inches and a 6 inch overhanging length was on both side. The subsequent results of the three point bending test with three different loading rates are discussed in the succeeding sections.

##### 4.2.1.1 Behavior of RPP at different loading rates

The stress-strain behavior of RPP at the loading rate of 0.5 kips/min., 2.7 kips/min. and 4.9 kips/min. is presented in Figure 4.1. Based on the experimental results, it was observed that the stress-strain curve followed the similar trend at the elastic range for the three different loading

rates. During the lower loading rate, the plastic pin had higher peak strength compared to the higher rate of loading. At the lower loading rate (0.5 kip/min), the curve presented a wide range of peak followed by plastic state at the tail. At 2.7 kip/min loading rate, a prominent peak was observed. At the highest loading rate (4.9 kip/min), no significant peak was observed. The stress-strain curve had a sharp change from the elastic state to the plastic state at the loading rate of 4.9 kip/min. Therefore, it could be mentioned that the plastic pin had significant plastic deformation at the higher loading rate compared to the lower rate of loading. The maximum peak strength and modulus of elasticity variations are presented in Figure 4.2.

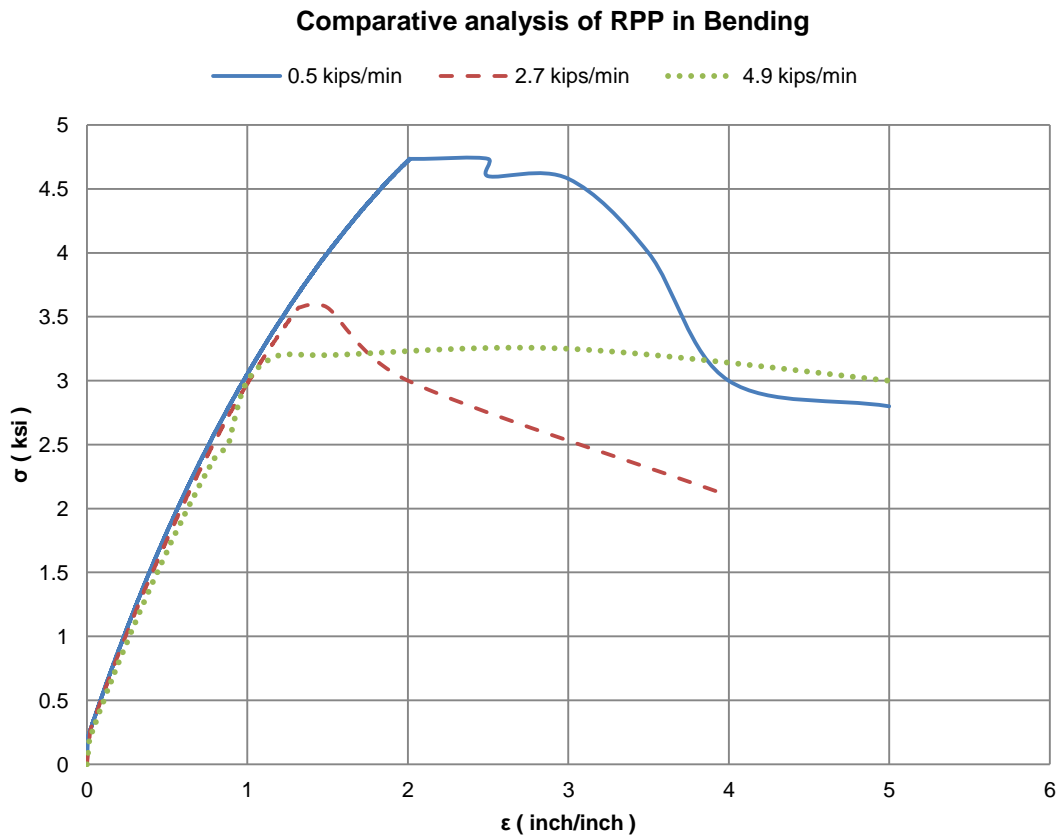
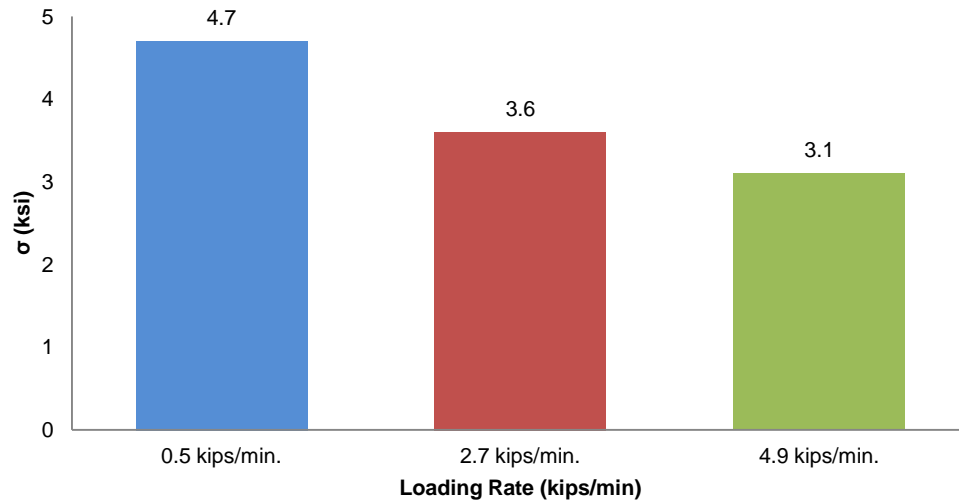
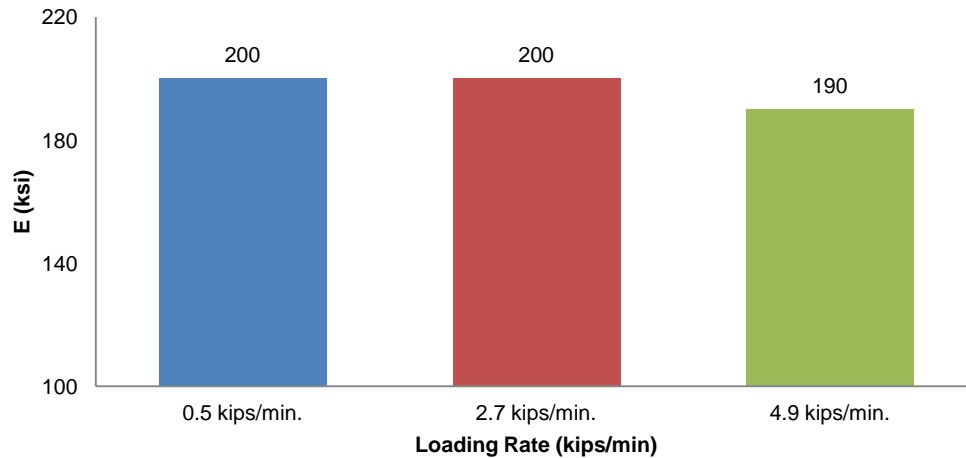


Figure 4.1: Stress-Strain response of RPP at different loading rates flexure



(a)



(b)

Figure 4.2: Flexural Strength variation with loading rates (a) Peak Strength Variation (b) Modulus of Elasticity Variation

It was observed that the variation in loading rate reflects that the maximum peak strength is inversely varied to the loading rate. However, the modulus of elasticity is fairly constant over the loading rates.

Bowders et al., (2003) performed a study on the flexure behavior of different manufacturing process of recycled plastic pin. During the study, the author used two different



RPP manufacturing types: compression molded and extruded, to analyze the effect of the constitutive process on the flexible behavior. The test result of the study is presented in Figure 4.3. The batch A4 was compression molded similar to the specimen used during the current study. The peak strength of the batch A4 sample was 2.5 ksi for the equivalent loading rate of 9.8 kip/min. The loading rate utilized by Bowders et al., (2003) was higher compared to the loading rate used during the current study. Therefore, it was expected that the peak strength should be lower compared to the peak strength observed for loading rate 4.9 kip/min. The observed peak strength at loading rate 9.8 kip/min was 2.5 ksi which was lower than the peak value of 3.1 ksi for loading rate 4.9 kip/min. Therefore, the results were in good agreement.

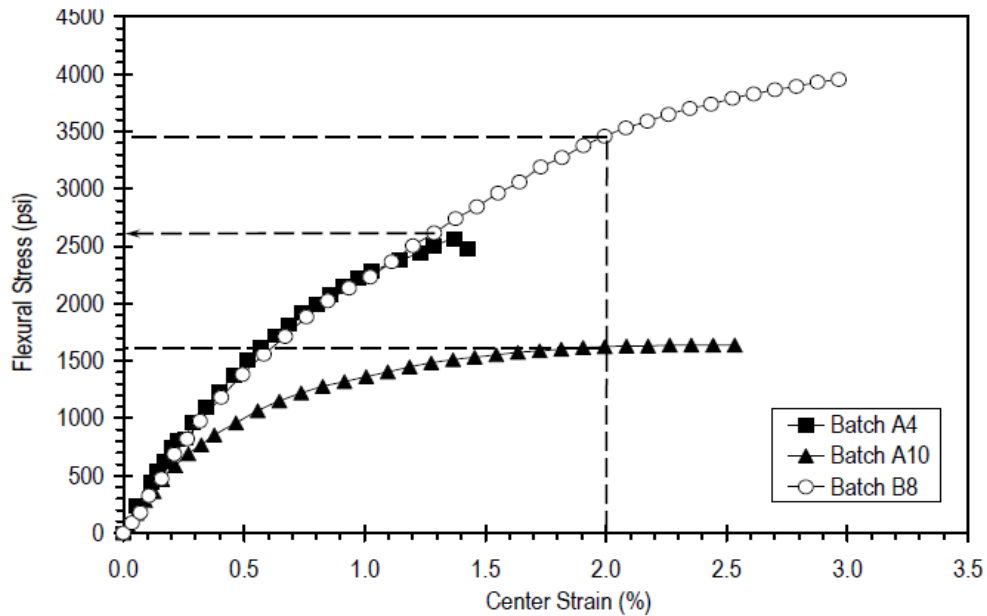


Figure 4.3: Stress-Strain curve for different RPPs in flexure ( Bowders et al., 2003)

#### 4.2.2 Wood

The total length of the wood sample was 68 inch similar to the length of the plastic pin. The subsequent results of the three point bending test with three different loading rates are discussed in the succeeding sections.

##### 4.2.2.1 Behavior of Wood at different loading rates

The stress-strain behavior of wood at 0.5 kips/min., 2.7 kips/min. and 4.9 kips/min. is presented in Figure 4.4. Based on the experimental results, it was observed that the failure pattern for 0.5 kips/min. and 4.9 kips/min. were similar where the sample had similar elastic state and no plastic deformation. In case of 2.7 kips/min loading rate, a longer plastic state was observed after the yield of the specimen is the stress-strain curve. The maximum peak strength and modulus of elasticity variations at 0.5 kips/min, 2.7 kips/min. and 4.9 kips/min. are shown in (a) and (b), respectively in Figure 4.5.

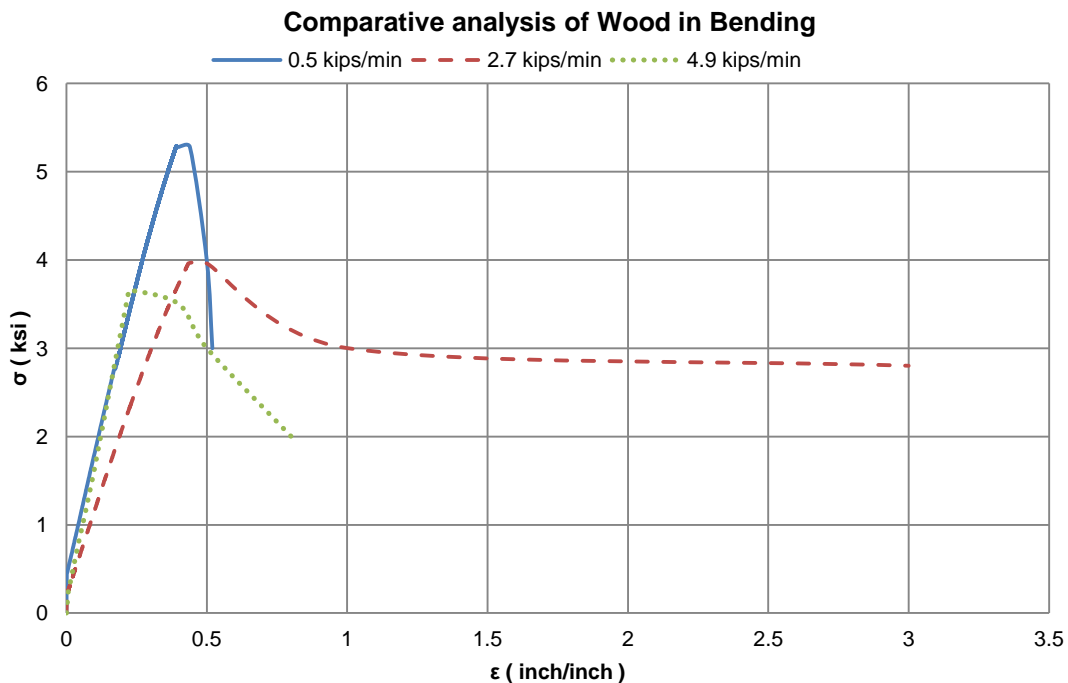
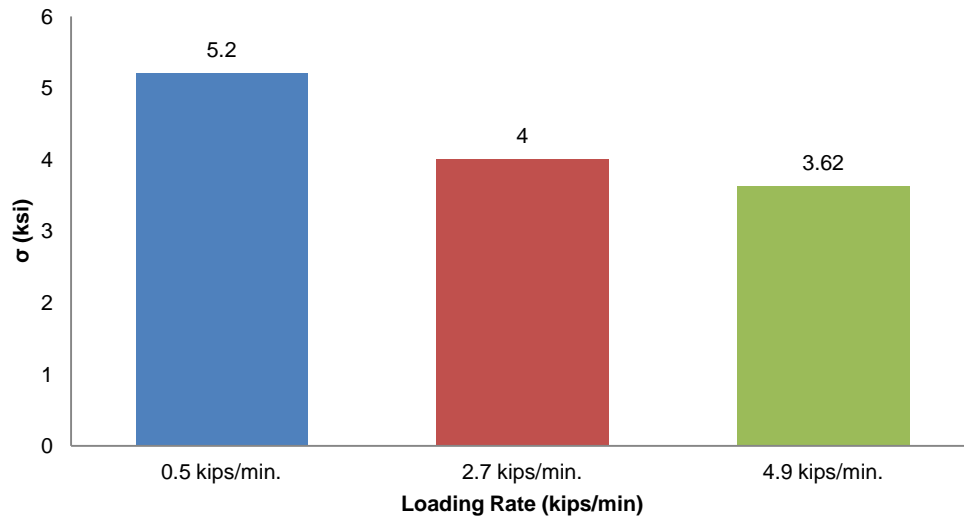
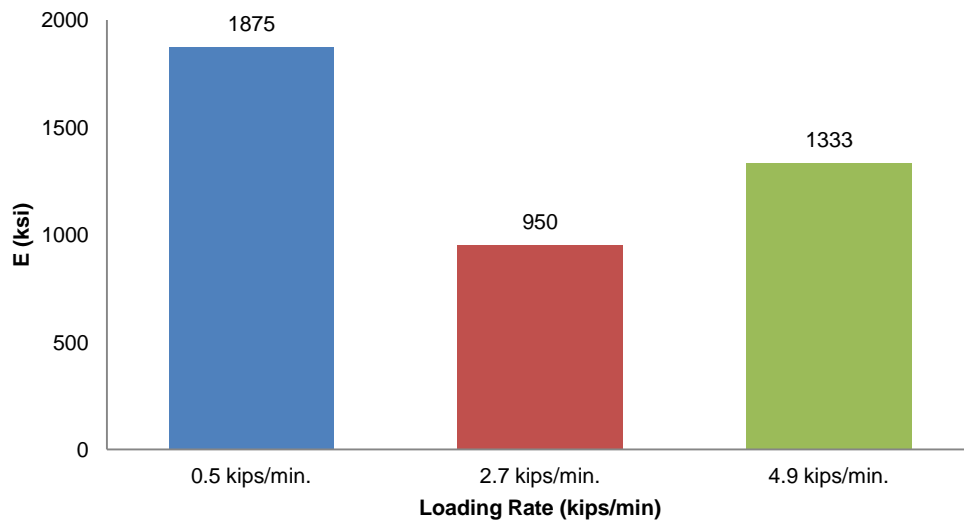


Figure 4.4: Stress-Strain response of Wood at different loading rates in flexure



(a)



(b)

Figure 4.5: Flexural Strength variation with loading rates (a) Peak Strength Variation (b) Modulus of Elasticity Variation

The variation in loading rate reflects that the maximum peak strength is inversely varied to the loading rate. Due to natural anisotropy, the flexural behavior and the modulus of elasticity variation was not uniform, over the loading rates.

### 4.2.3 Bamboo

The diameter of the bamboo pole varied from 3 inch at top and 4 inch at the bottom. The average diameter was taken to be 3.5 inch. The length of the sample was 68 inch where 56 inch was the support length during the 3 point bending test. The subsequent test results with 3 different loading rates for the bamboo poles are presented below.

#### 4.2.3.1 Behavior of Bamboo at different loading rates

The stress-strain behavior of bamboo at 0.5 kips/min., 2.7 kips/min. and 4.9 kips/min. is shown in Figure 4.6. Based on the experimental results, it was observed from the stress-strain curve that the bamboo failed in similar way, at the loading rate 2.7 kips/min. and 4.9 kips/min. However, but the specimen failed suddenly at higher loading rate of 0.5 kips/min. The maximum peak strength and modulus of elasticity variations at 0.5 kips/min, 2.7 kips/min. and 4.9 kips/min. are shown in (a) and (b), respectively in Figure 4.7.

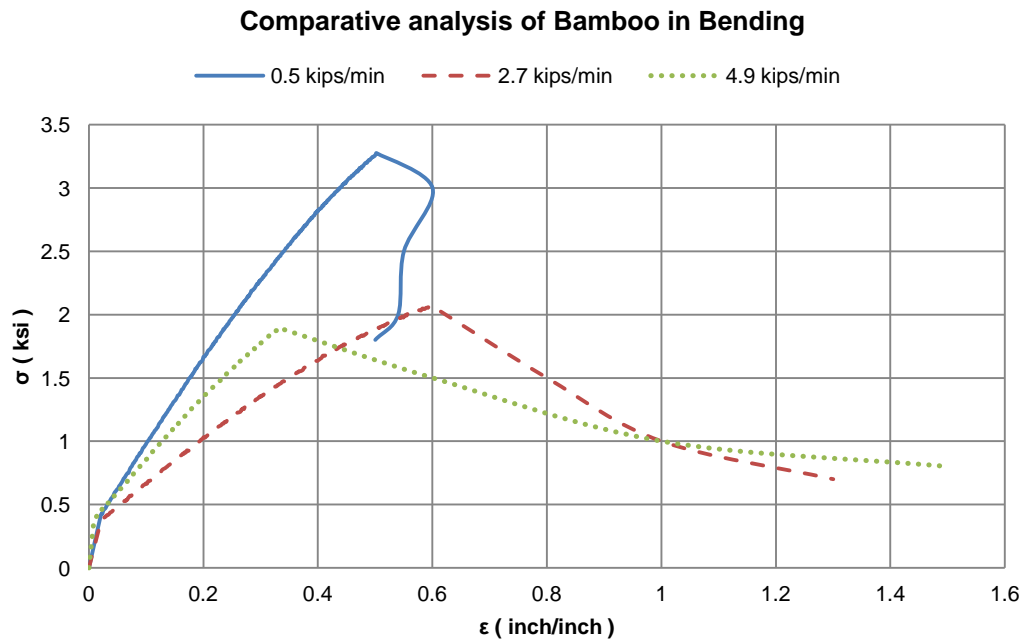
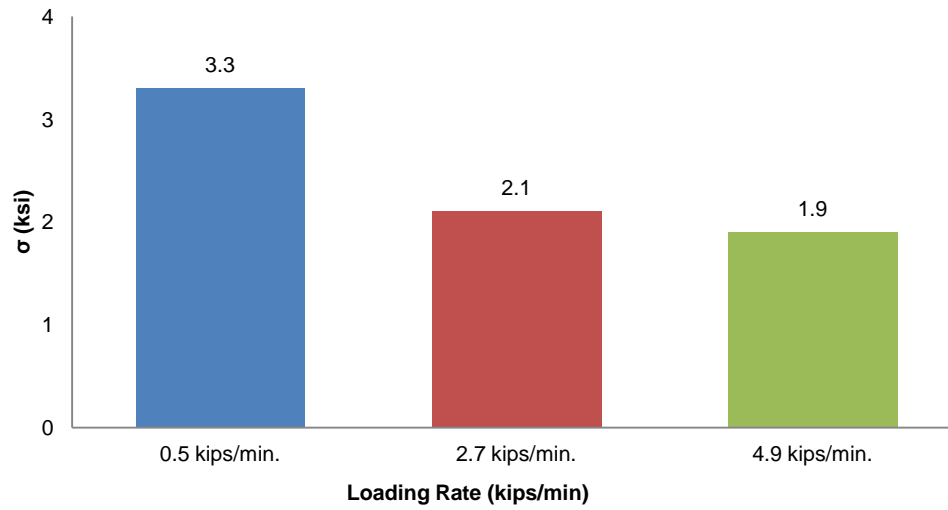
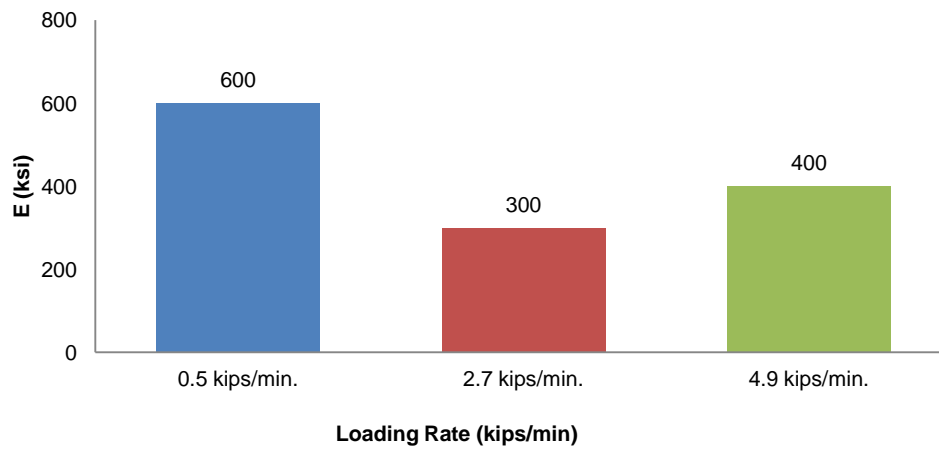


Figure 4.6: Stress-Strain response of Bamboo at different loading rates in flexure



(a)



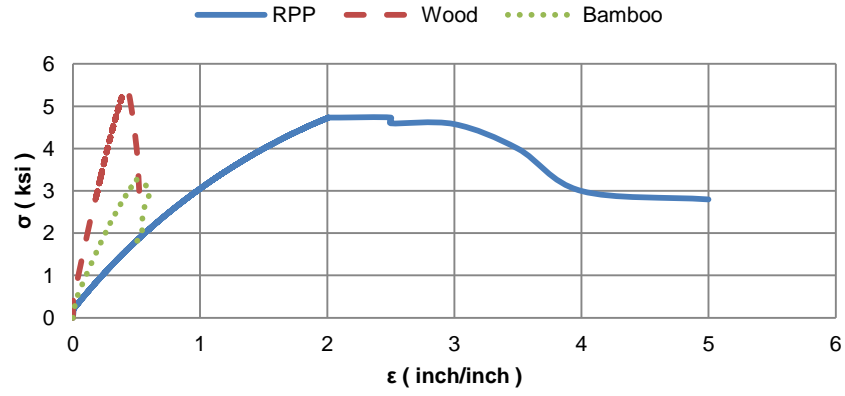
(b)

Figure 4.7: Flexural Strength variation with loading rates (a) Peak Strength Variation (b) Modulus of Elasticity Variation

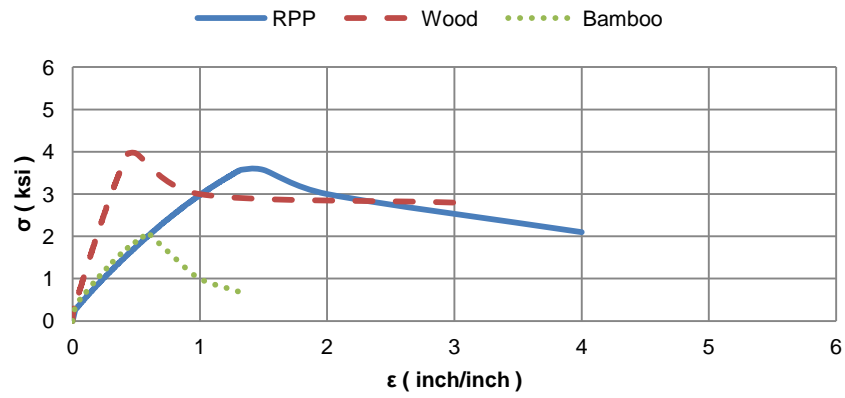
The variation in loading rate reflects that the maximum peak strength is inversely varied to the loading rate. The flexural behavior varied significantly due to natural anisotropy, but the modulus of elasticity was fairly constant, over the loading rates.

#### 4.2.4 Comparison at different loading conditions

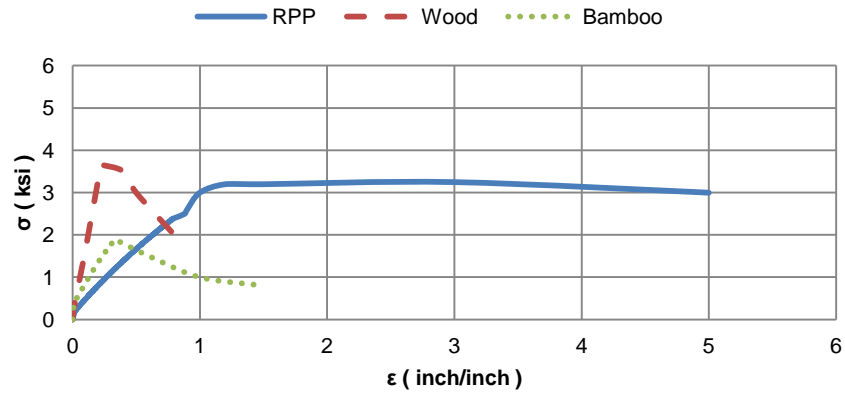
The flexural behavior of RPP, Wood and Bamboo at the loading rate of 0.5 kips/min, 2.7 kips min. and 4.9 kip/min. are presented in Figure 4.8. The photos of the failure mode of the different materials are presented in Figure 4.9. It was observed from the flexure test results of RPP, wood lumber and bamboo in all the loading rates that RPPs showed more consistent plastic state. The failure strain for RPP was around 1-2% where the failure strain of wood and bamboo was around 0.5%. Furthermore, in flexure, RPP exhibits more elastic behavior compared to wood and bamboo. Bamboo exhibits more flexibility than wood. It is noticed from the graph, after a limiting strain in all the rates, wood and bamboo yields where RPP extends to more elastic behavior. It signifies that RPP will be more suited to slope failure conditions which occurs due to large soil movement. The variation of peak strength and modulus of elasticity of RPP, wood and bamboo poles are presented in Figure 4.10 and Figure 4.11, respectively.



(a)



(b)

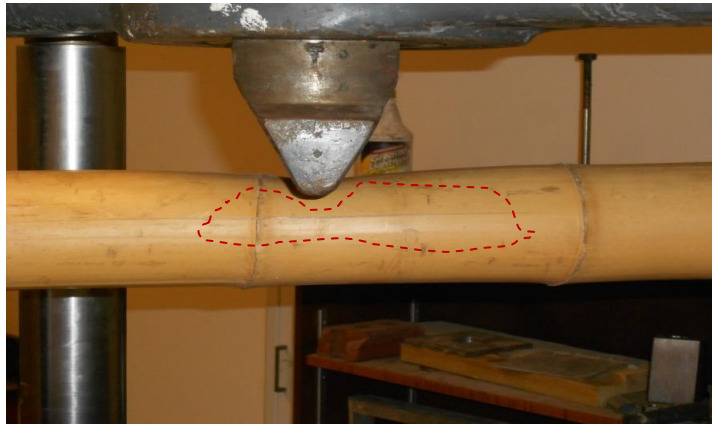


(c)

Figure 4.8: Flexural variation of stress-strain with different loading rates (a) 0.5 kips/min (b) 2.7 kips/min (c) 4.9 kips/min.



(a)



(b)



(c)

Figure 4.9: Three Point Bending Test (a) RPP (b) Bamboo (c) Wood



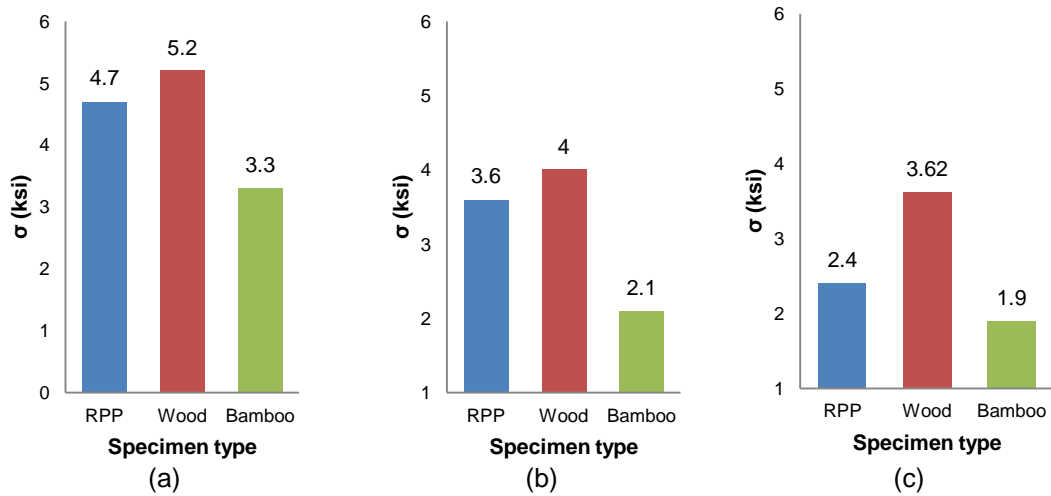


Figure 4.10: Variation of Peak strength with different loading rates (a) 0.5 kips/min (b) 2.7 kips/min (c) 4.9 kips/min.

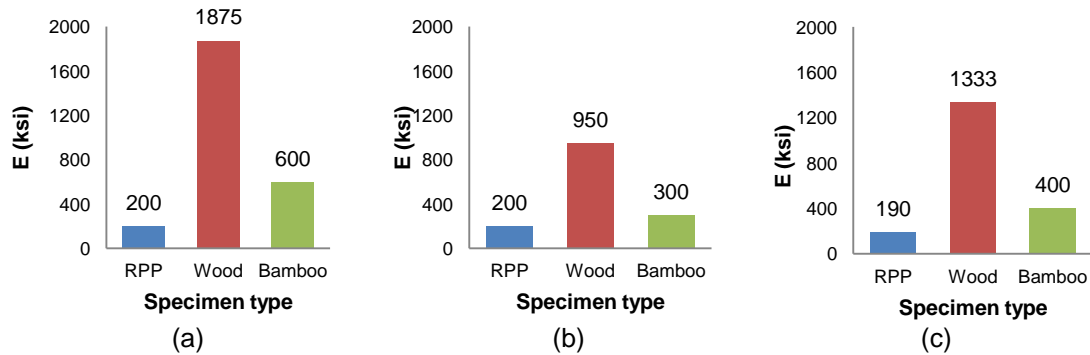


Figure 4.11: Variation of Modulus of Elasticity with different loading rates (a) 0.5 kips/min (b) 2.7 kips/min (c) 4.9 kips/min.

Considering the peak strength, wood exhibits higher peak value than RPP and bamboo. If we observe the pattern of the modulus of elasticity for different specimen, it was observed that wood has higher modulus of elasticity, as compared with the others, which signifies wood is more flexural stiffer.

Based on the above discussion and the 3 point loading test results with different loading rates of RPP, wood and bamboo, it can be concluded that,

- Wood exhibits stiffer behavior.
- Bamboo is flexibly less stiff than wood.
- RPP is more ductile than the other two.
- After 0.5% strain, wood and bamboo fails where RPP continues to thrive.
- The modulus of elasticity is more consistent in RPP.
- The peak strength at the highest loading rate is the lowest for all three materials.

#### 4.3 Uniaxial Compression Test

The uniaxial compression tests were conducted at three different strain rate, 0.004 in/in/min, 0.005 in/in/min, 0.006 in/in/min. The tests were conducted at the testing facility where the loading rate can be controlled instead of the strain rate. Therefore the equivalent loading rate was calculated and the tests were conducted. The equivalent loading rate was at 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min respectively. Each test was conducted until the specimen fails to accommodate the applied loading rates. Since the approach was to compare wood and bamboo with respect to RPP, for transforming the strain to the loading rates, the modulus of elasticity of RPP was considered as provided by the manufacturer ( Bedford Technology, 2011).

##### 4.3.1 Without Environment effects

The initial tests were performed on the samples that have no environmental effects. The length of each sample was selected as the 2 times of the minimum width of the specimen. Therefore the length of the specimen was 7 inches. The subsequent results of the three loading rates, for each sample, are discussed in the succeeding sections.

##### 4.3.1.1 Behavior of RPP at different axial loading rates

The stress-strain curve of RPP at 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min. is showed in Figure 4.12. It was observed from the graph that, at the lowest loading rate, the stress-strain curve shows yielding after 15% strain. The failure trend indicated that at 2.5 kips/min. and 3.1 kips/min. loading rate, the failure was sudden. On the other hand, for 3.75 kips/min. loading

rate, a prolonged failure trend was observed. The peak strength and modulus of elasticity variation at the above mentioned loading rates are shown in Figure 4.13.

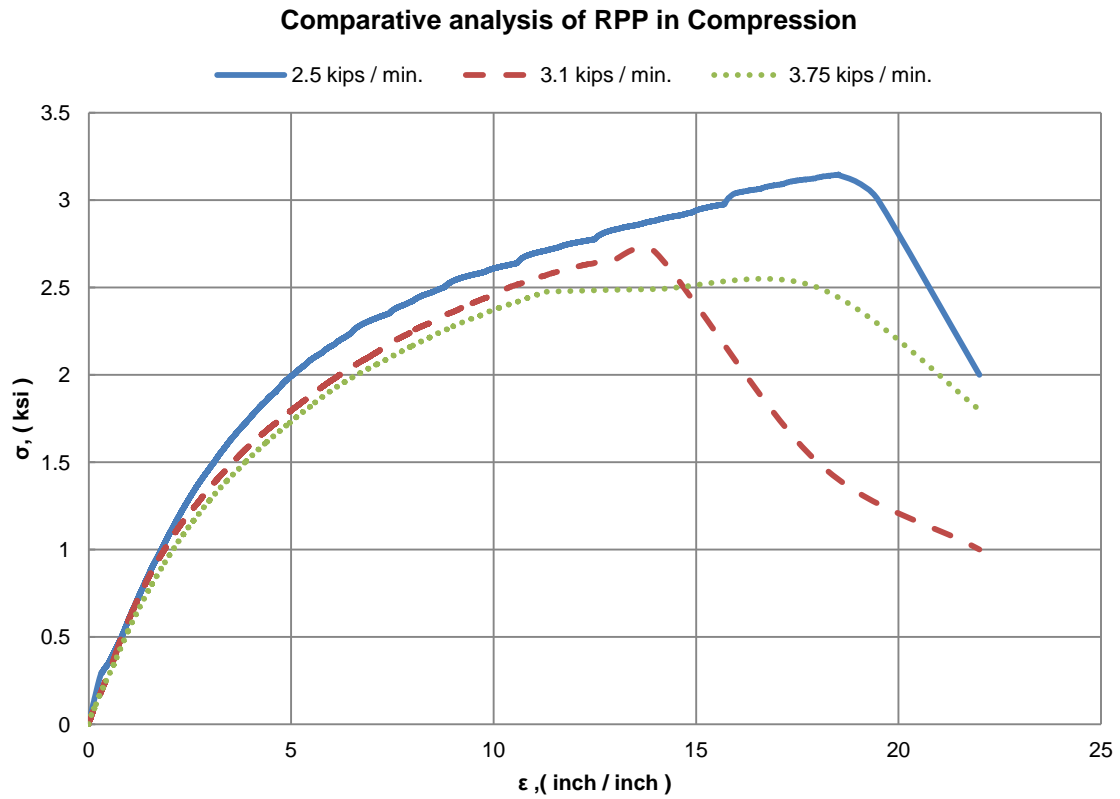
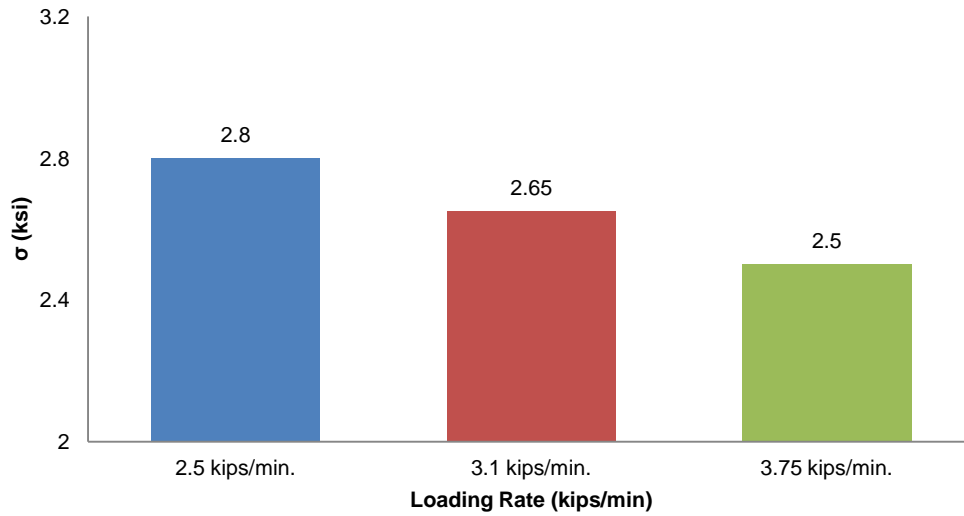
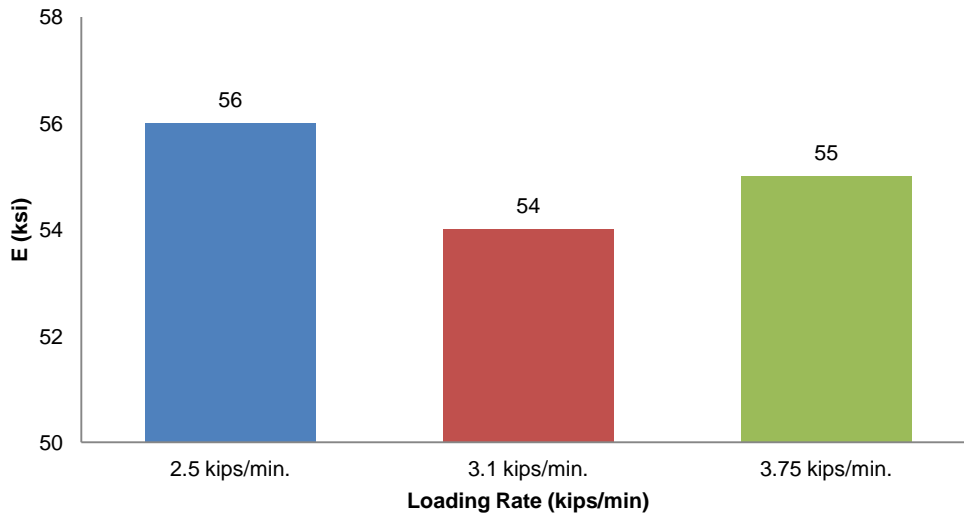


Figure 4.12: Stress-Strain response of RPP at different loading rates W/O Degradation



(a)



(b)

Figure 4.13: Axial Strength variation with loading rates (a) Peak strength variation (b) Modulus of Elasticity variation

From Figure 4.13, the peak compressive strength of the RPP was 2.8 ksi, 2.65 ksi and 2.5 ksi for the loading rate of 2.5 kip/min, 3.1 kip/min and 3.75 kip/min respectively. In addition, the elastic modulus from compression of the RPP was 56, 54 and 55 ksi for the loading rate of 2.5 kip/min, 3.1 kip/min and 3.75 kip/min respectively. Based on the compression test result, it was observed that the maximum peak strength and the flexural behavior are inversely varied to the loading rate.

However, the modulus of elasticity is fairly constant over the loading rates. Bowders et al., 2003 studied the effect of molding process on the compressive strength of RPP. During the study, the author conducted the axial compressive test at a constant strain rate of 0.006 inch/min. The axial strength test result of the study is presented in Figure 4.13. During the current research, the compression molded specimen was utilized similar to batch A4 as presented in Figure 4.14.

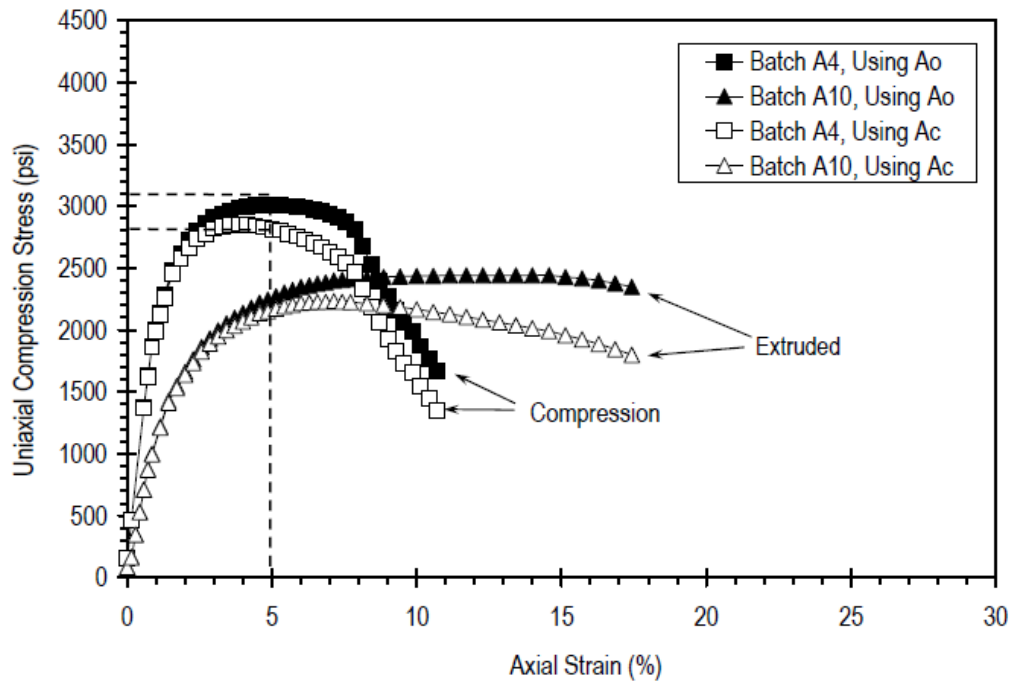


Figure 4.14: Axial stress-strain curve ( Bowders et al., 2003)

It was observed from their results that the Batch A4, which was compression molded similar to the type used in the current research, showed peak strength of 3.0 ksi which is more than the peak value of 2.5 ksi at the same strain rate in the current study, considering original area ( $A_0$ ) only. The variation might be due to the different of the constitutive materials.

#### 4.3.1.2 Behavior of Wood at different axial loading rates

The stress-strain effect of wood at 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min. is shown in the Figure 4.15. The peak strength and modulus of elasticity variation at the above mentioned loading rates are shown in Figure 4.16.

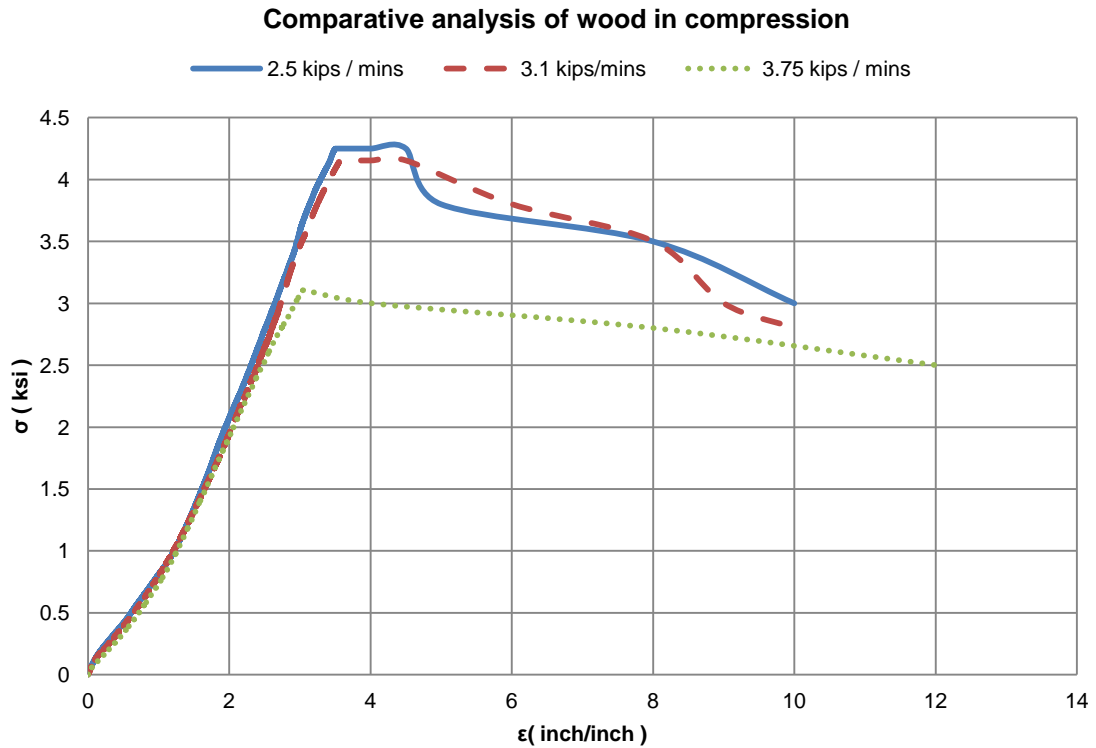
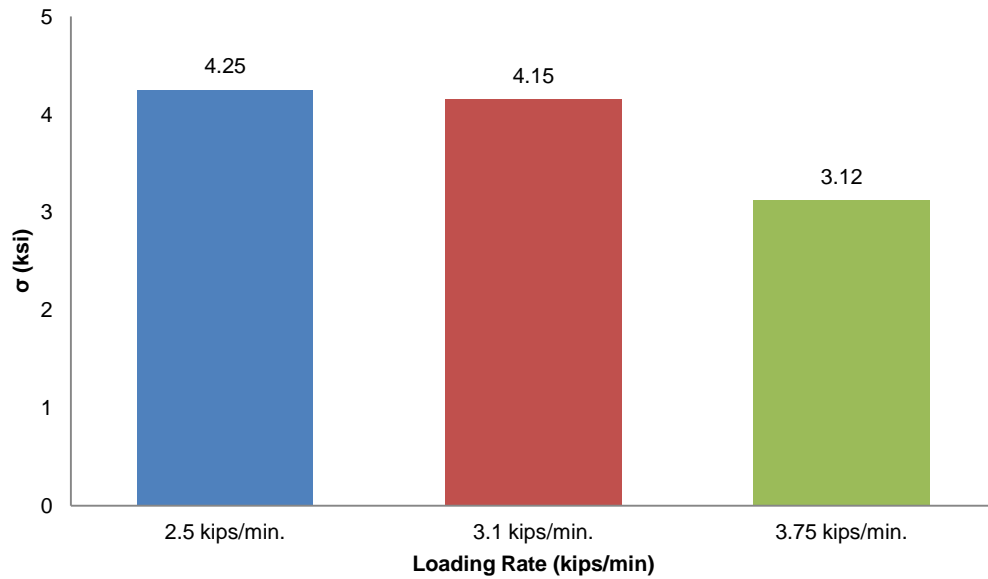
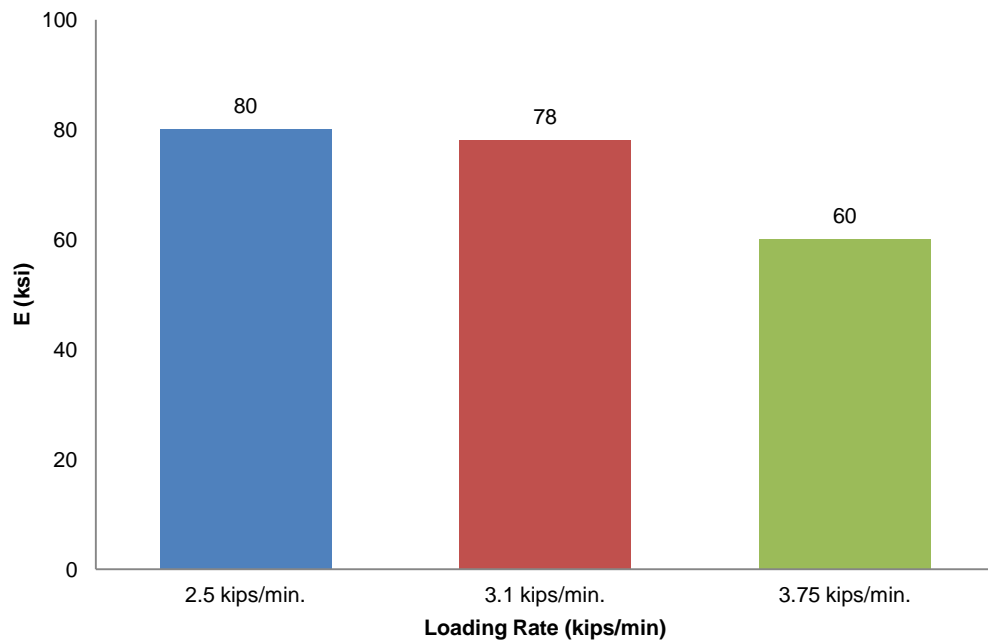


Figure 4.15: Stress-Strain response of Wood at different loading rates W/O Degradation



(a)



(b)

Figure 4.16: Axial Strength variation with loading rates (a) Peak Strength Variation (b) Modulus of Elasticity Variation

From Figure 4.16, the peak compressive strength of the wood was 4.25 ksi, 4.15ksi and 3.12 ksi for the loading rate of 2.5 kip/min, 3.1 kip/min and 3.75 kip/min respectively. In addition, the

elastic modulus from compression of the RPP was 80, 78 and 60 ksi for the loading rate of 2.5 kip/min, 3.1 kip/min and 3.75 kip/min respectively. It was observed that the peak strength and the elastic modulus were very close for the loading rate of 2.5 kip/min and 3.1 kip/min. However, the compressive strength reduced for the higher loading rate.

#### 4.3.1.3 Behavior of Bamboo at different axial loading rates

The stress-strain effect of Bamboo at 2.5 kips/min, 3.1 kips/min. and 3.75 kips/min. is shown in the Figure 4.17. The peak strength and modulus of elasticity variation at the 3 different loading rates are shown in Figure 4.18.

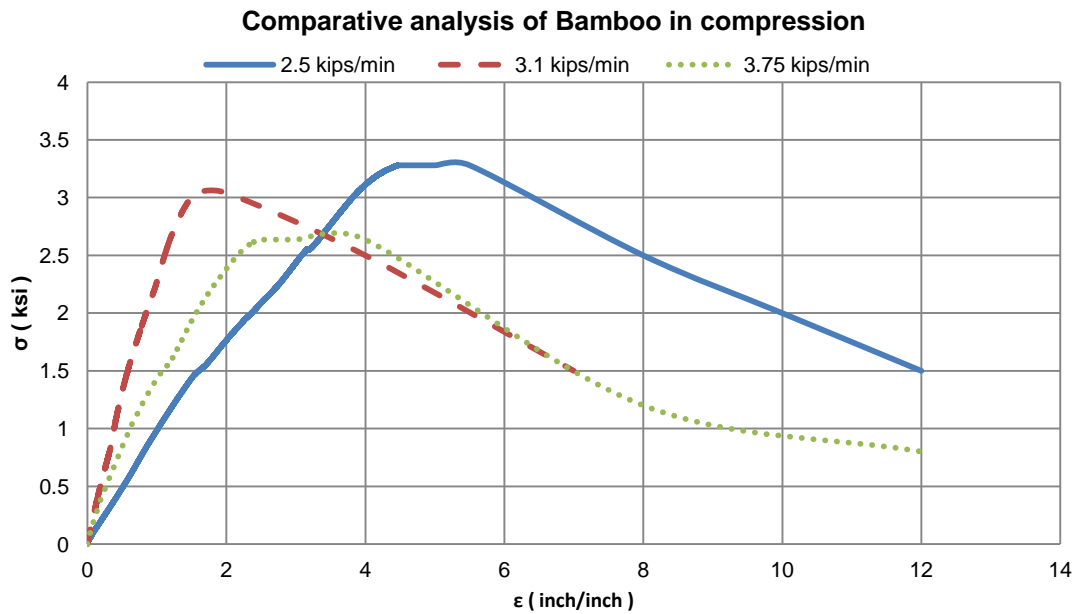
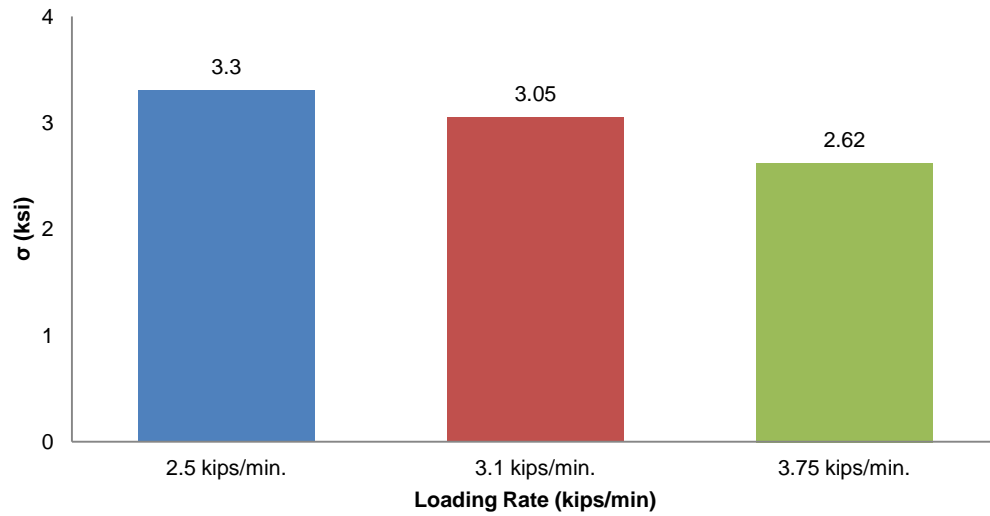
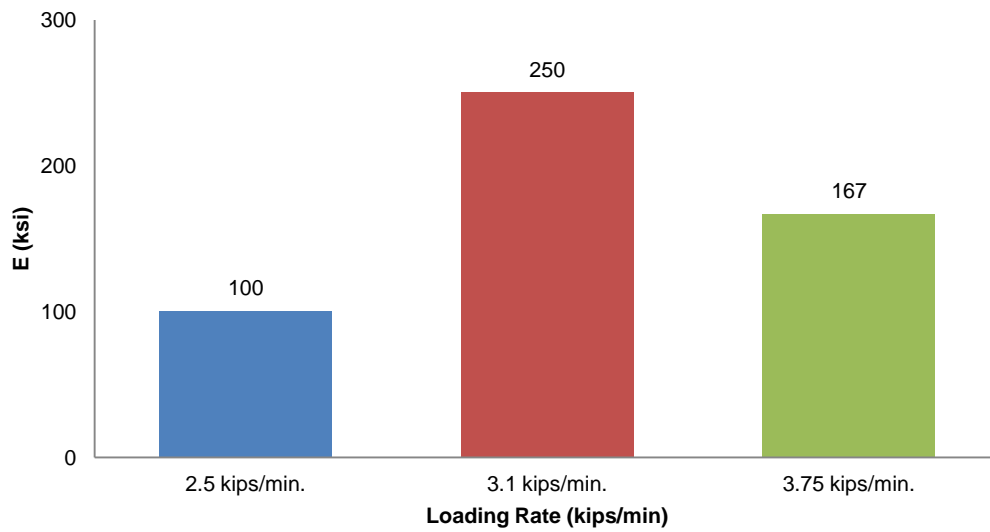


Figure 4.17: Stress-Strain response of Bamboo at different loading rates W/O Degradation





(a)



(b)

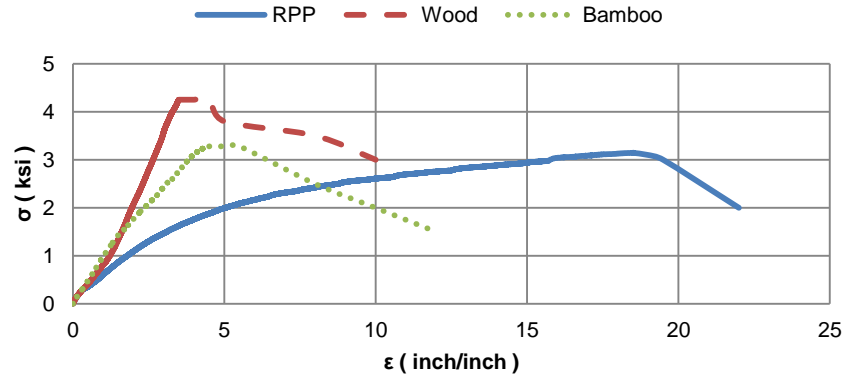
Figure 4.18: Axial Strength variation with loading rates (a) Peak Strength Variation (b) Modulus of Elasticity Variation

From Figure 4.17 and Figure 4.18, the peak compressive strength of the bamboo was 3.3 ksi, 3.05 ksi and 2.62 ksi for the loading rate of 2.5 kip/min, 3.1 kip/min and 3.75 kip/min respectively. In addition, the elastic modulus from compression of the RPP was 100, 250 and 167 ksi for the loading rate of 2.5 kip/min, 3.1 kip/min and 3.75 kip/min respectively. It was observed that the

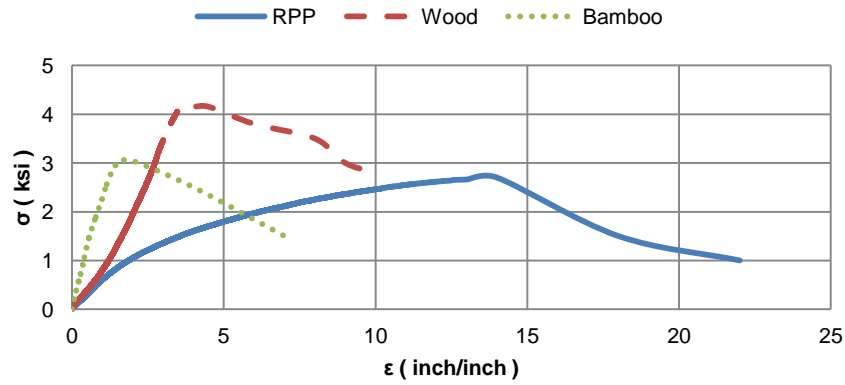
peak axial strength decrease with the increase in loading rate similar to RPP and Wood. However, elastic modulus for compression was observed erratic with the increasing loading rate. The erratic behavior of the elastic modulus might take place due to the natural anisotropy of the bamboo.

#### 4.3.1.4 Comparison of different specimen at different axial loading rates

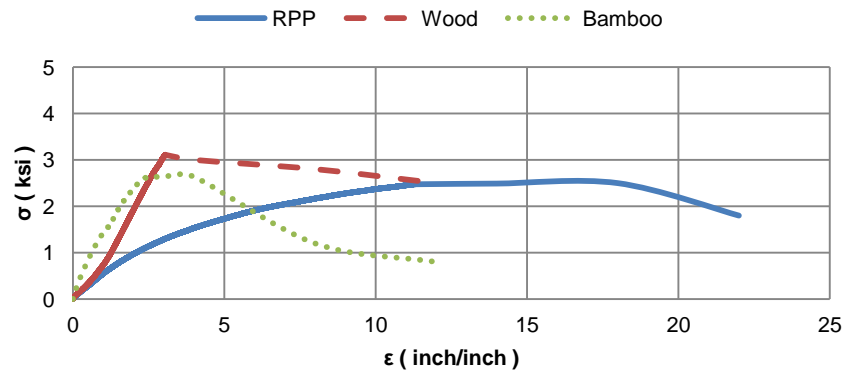
The axial behavior of RPP, Wood and Bamboo at 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min., in normal conditions, is shown in Figure 4.19. It was observed wood and bamboo specimen had prominent yielding point compared to RPP. In addition, the wood and bamboo had higher elasticity as the stress strain curve had steeper slope before yield. The different failure pattern of RPP, Wood and bamboo specimen is presented in Figure 4.19. The RPP specimen contracted with higher plastic settlement during the application of the axial compressive load as presented in Figure 4.19 (a). This plastic deformation was also observed in Figure 4.18 compared to the other specimen. On the contrary, no plastic deformation was observed for wood and bamboo. The bamboo and wood sample cracked along the axial direction and failure due to the application of axial compressive load. The comparison of Peak strength and elastic modulus of RPP, wood and bamboo is presented in Figure 4.21 and Figure 4.22, respectively.



(a)



(b)



(c)

Figure 4.19: Axial variation of stress-strain with different axial rates W/O Degradation (a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.



(a) Before



(a) After



(b) Before



(b) After



(c) Before



(c) After

Figure 4.20 : Comparative diagrams in compression W/O degradation (a) RPP (b) Bamboo (c) Wood

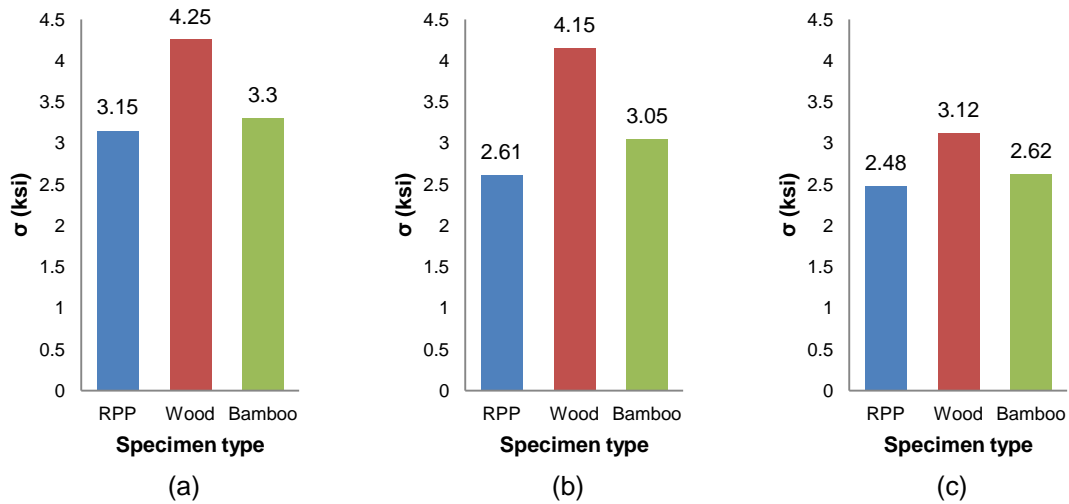


Figure 4.21: Variation of Peak strength with different loading rates W/O Degradation (a) 2.5 kip/min. (b) 3.1 kips/min. (c) 3.75 kips/min

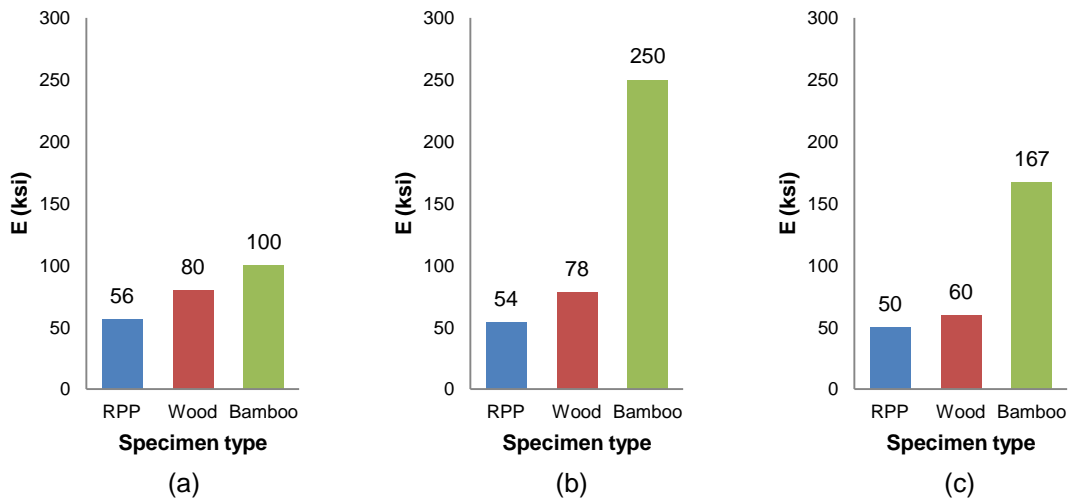


Figure 4.22: Variation of Modulus of Elasticity with different loading rates W/O Degradation (a) 2.5 kip/min. (b) 3.1 kips/min. (c) 3.75 kips/min

The wood sample had higher peak and elastic modulus followed by RPP and Bamboo. RPP had higher peak strength compared to bamboo in each loading rate. However, the elastic modulus for RPP was observed lower compared to the bamboo. With the increase of loading rate, the elastic modulus for compression varies for wood and bamboo. It can be mentioned that the variation takes place due to the natural anisotropy.

Based on the laboratory investigation for axial compression, the major findings can be concluded as follows.

- Wood possesses higher peak strength in all conditions
- RPP exhibits more ductility.
- The modulus of elasticity of bamboo is the highest in all loading rates.
- Bamboo and wood limits to particular strain in all rates where RPP continues to thrive.

#### 4.3.2 Considering effects of Environment

For the environment tests, the samples from each specimen were submerged for two months and the tests were performed with the same loading rates as that of the non-environment conditions to simulate the effect of the environment change. The length of each samples was 7 inches same as the length of the specimen for normal condition. The subsequent results of the three loading rates, for each sample, are discussed in the succeeding sections.

##### 4.3.2.1 At pH < 7.0 solution

To simulate the effect of Texas red-clay, comprising of a pH value of 5.5 (Kellenberg, 2000), the samples were submerged in HCL solution for two months. Red clay is technically, subsoil, and is derived from the erosion of topsoil. Its origin is found to be due to improper agricultural practices and soil-stripping development of rural areas. Red clay soil is sticky and thick when wet and rock hard when dry. The color is derived due to the presence of iron oxides. Red clay soil is found in dry areas, such as Texas, and is hard to cultivate. Red clay is considered undesirable and causes stains on clothing upon contact. The submerged samples were observed weekly whether there is a drop in pH and corrective measures were taken accordingly.

#### 4.3.2.1.1 Behavior of RPP at different axial loading rates

The stress-strain effect of RPP at 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min., in acidic conditions, is shown in Figure 4.23. It was observed from the compressive behavior of RPP in acidic conditions that the failure behavior at all loading rates were similar and it was gradual. The peak strength and modulus of elasticity variation at the above mentioned loading rates are shown in Figure 4.24.

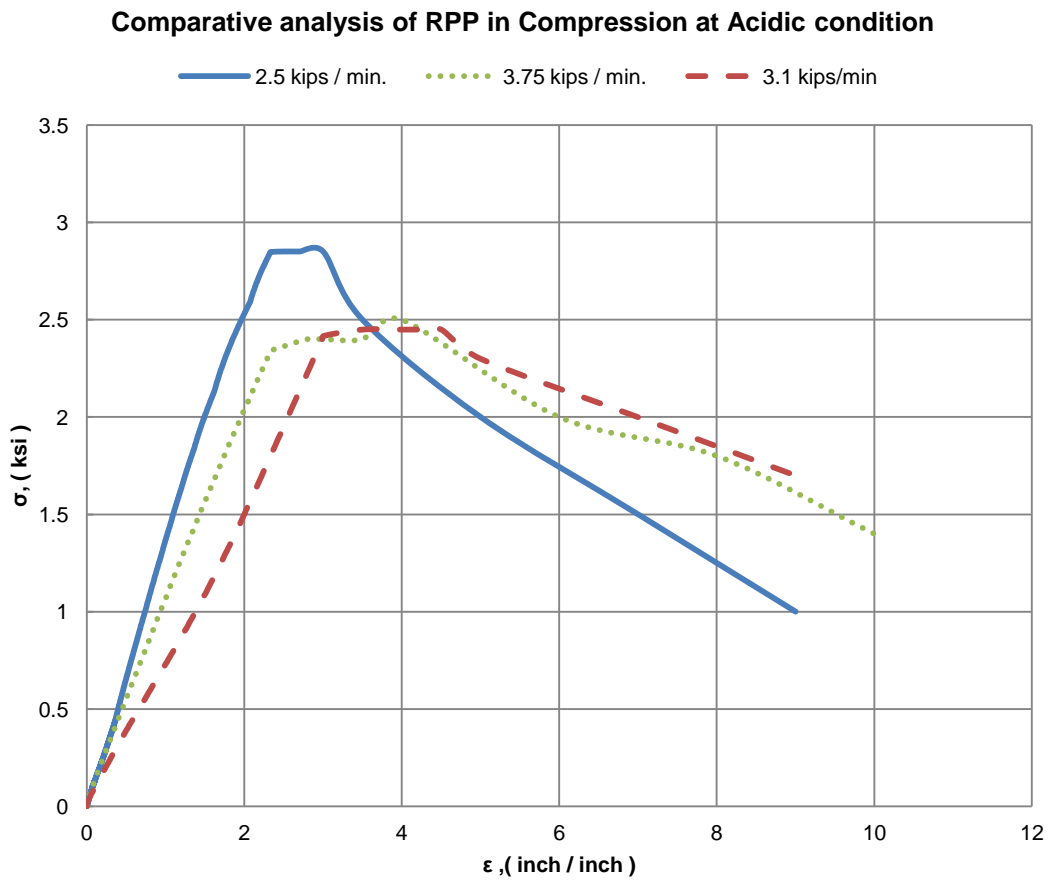
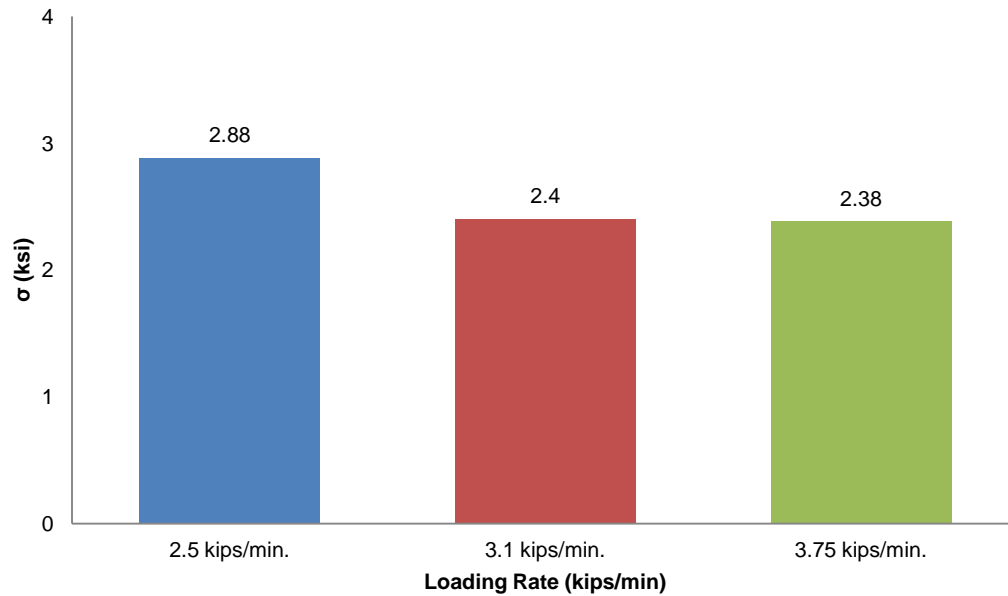
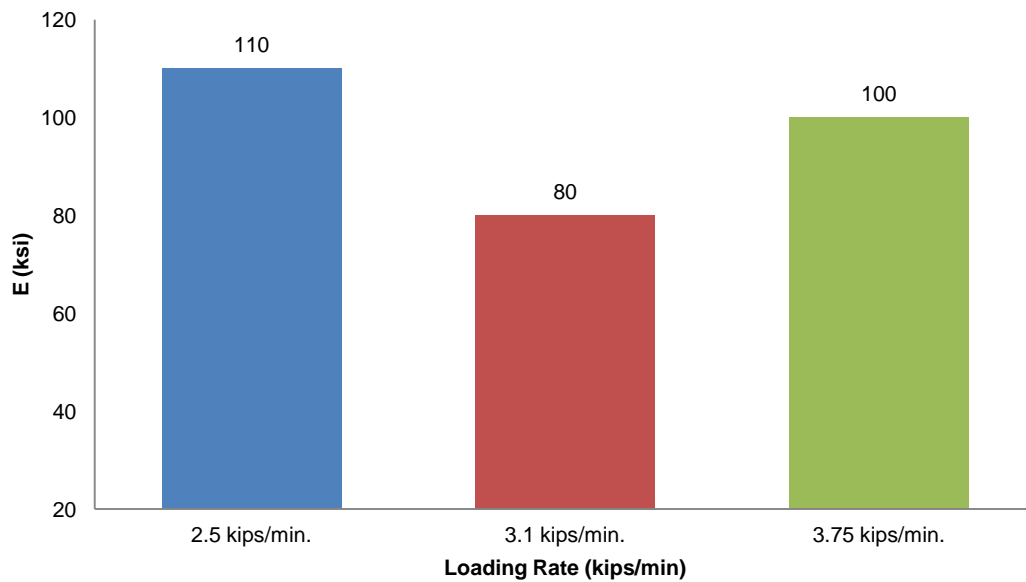


Figure 4.23: Stress-Strain response of RPP at different loading rates in Acidic condition



(a)



(b)

Figure 4.24: Axial Strength variation with loading rates in Acidic Conditions (a) Peak strength variation (b) Modulus of elasticity variation

Based on the laboratory investigation, RPP had higher compressive strength at lower loading rate. However, the peak axial compressive strength is very close for the higher loading rate of 3.1 kip/min and 3.75 kip/min. The variation in loading rate reflects that the maximum peak strength is



inversely varied to the loading rate. The flexural behavior is different from the non-environment conditions, which is lowest at the low loading rate. The modulus of elasticity is fairly constant over the loading rates. The various loading rates will reflect the field applied rates, during installation, with the vertical component of the inclined slope loading from in-situ conditions and the peak strength will exhibit accordingly.

#### 4.3.2.1.2 Behavior of Wood at different axial loading rates

The stress-strain effect of wood at 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min., in acidic conditions, is shown in the Figure 4.25. The stress-strain curve of wood, in compression with acidic condition, showed similar and prolonged failure trends. The failure strain for the loading rate 2.5 kips/min. and 3.1 kips/min. was 2% whereas for loading rate 3.75 kips/min., the failure strain was 8%. It might imply that, in acidic condition, wood shows more plastic behavior in high load rates or, worse slope movements. The peak axial compressive strength and modulus of elasticity variation at the above mentioned loading rates are shown in Figure 4.26.

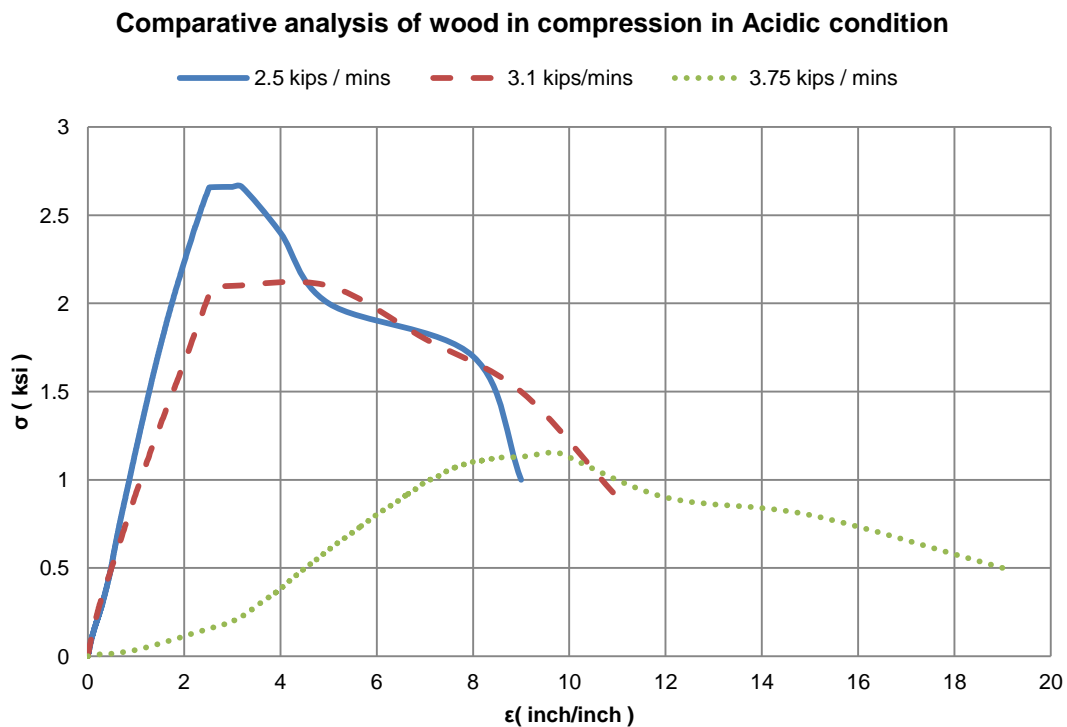
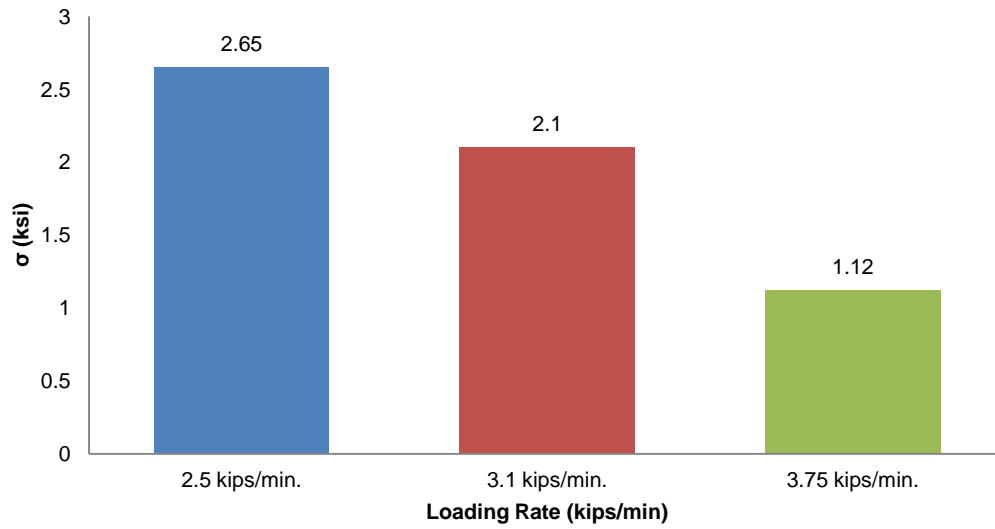
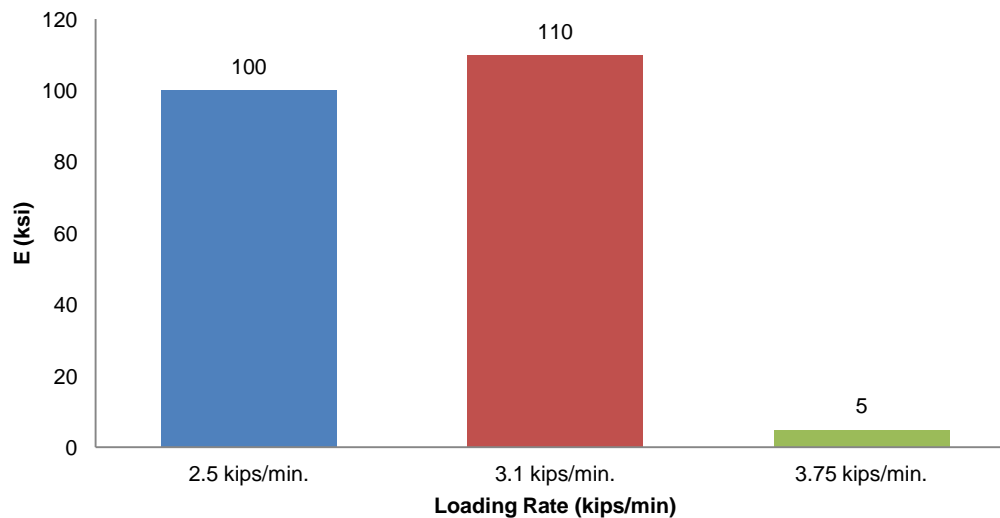


Figure 4.25: Stress-Strain response of Wood at different loading rates in Acidic condition



(a)



(b)

Figure 4.26: Axial Strength variation with loading rates in Acidic Conditions (a) Peak strength variation (b) Modulus of Elasticity Variation

The variation in loading rate reflects that the maximum peak axial compressive strength is inversely varied to the loading rate. In addition, the elastic modulus at the higher loading rate was

very low compared to the lower loading rate. It may signify that due to high loading rate, the wood fails to internal degradations caused by the acidic environment.

#### 4.3.2.1.3 Behavior of Bamboo at different axial loading rates

The stress-strain effect of bamboo at 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min., in acidic conditions, is shown in the Figure 4.27. It was observed from the stress-strain curve that failure strain was highest at the lowest loading rate. The failure strain was 2.5%, 0.75% and 1.2% for the loading rate 2.5 kips/min. 3.1 kips/min. and 3.75 kips/min respectively. The peak strength and modulus of elasticity variation at the different loading rates are shown in Figure 4.28.

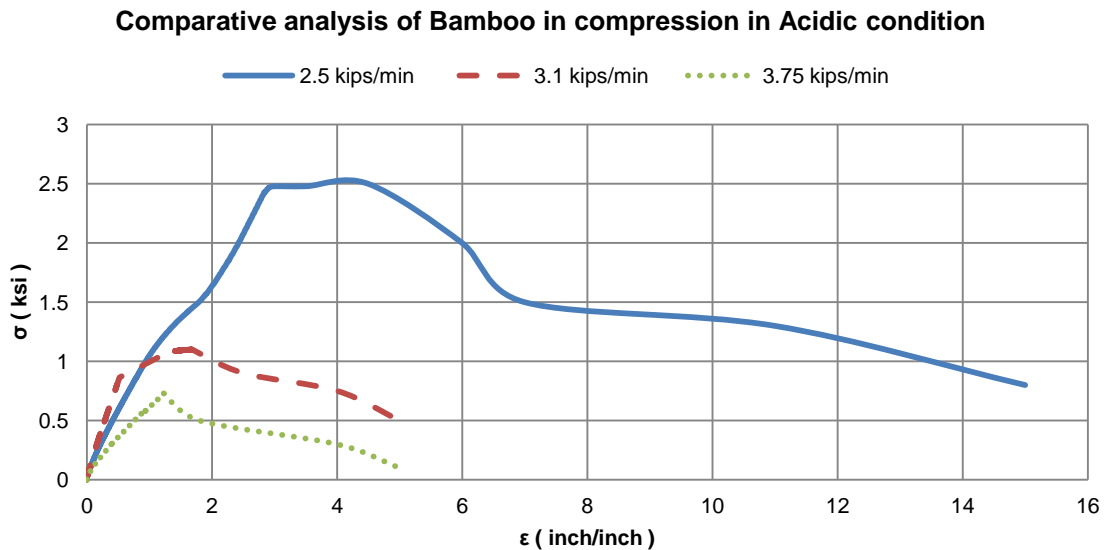
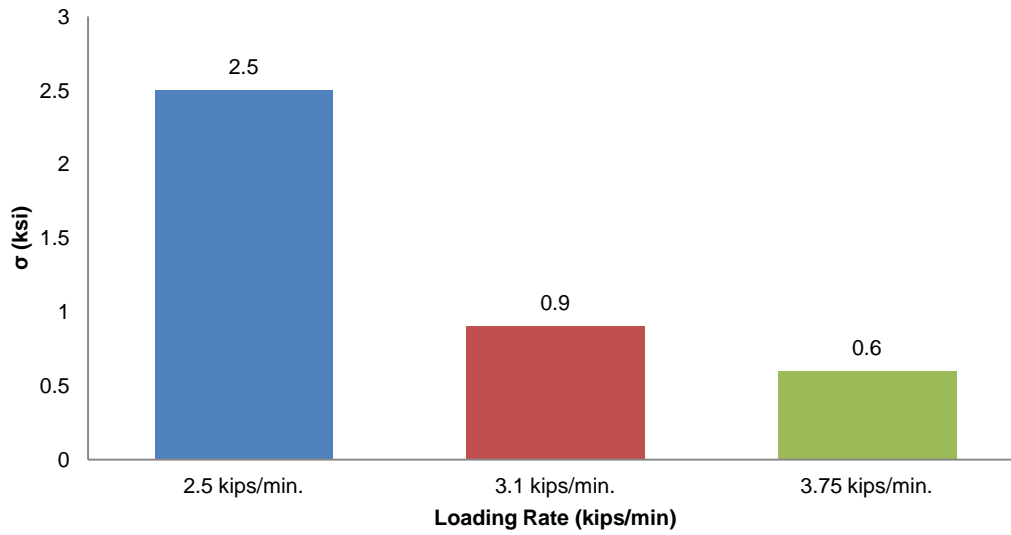
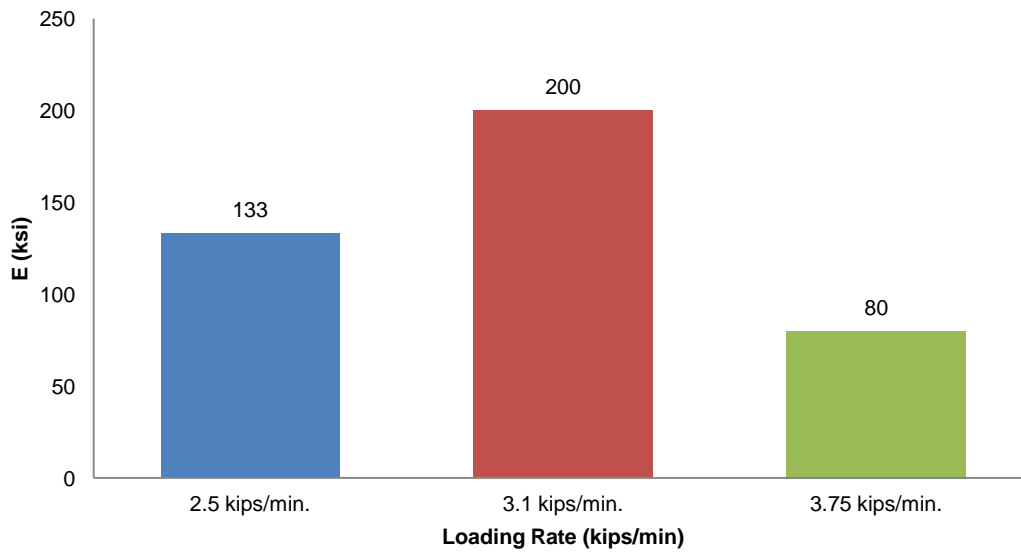


Figure 4.27: Stress-Strain response of Bamboo at different loading rates in Acidic condition



(a)



(b)

Figure 4.28: Axial Strength variation with loading rates in Acidic Conditions (a) Peak strength variation (b) Modulus of Elasticity Variation

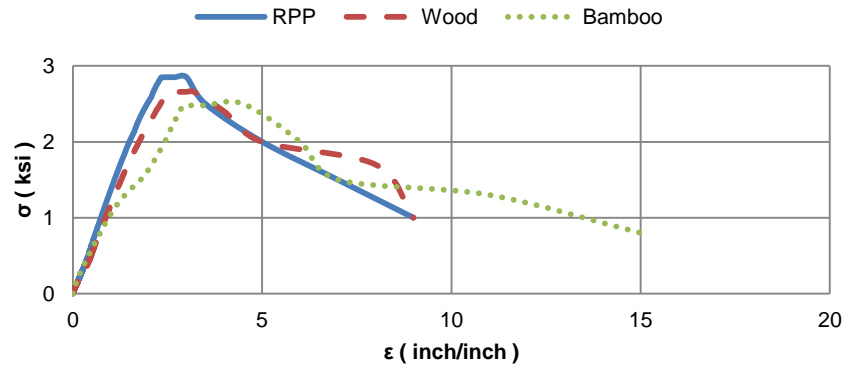
The peak compressive strength was higher for the loading rate 2.5 kip/min comparative to the loading rate 3.1 kip/min and 3.75 kip/min. The compressive axial strength at the higher loading rate (3.1 kip/min and 3.5 kip/min) was observed very close. This trend for bamboo was observed similar to the variation for wood specimen at the acidic condition. The elastic modulus in

compression was observed erratic with varying loading rate. The modulus of elasticity showed to be highest at 3.1 kips/min and lowest at 3.75 kips/min. The erratic behavior may signify the natural anisotropy of the bamboo pole.

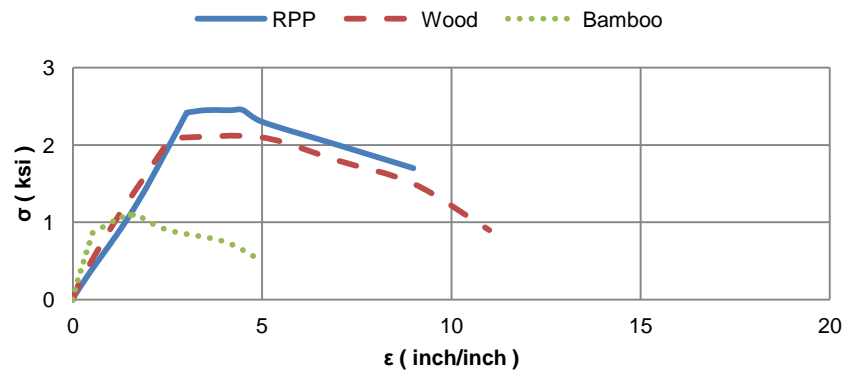
#### 4.3.2.1.4 Comparison of different specimen in acidic conditions at different axial rates

The axial compressive behavior of RPP, Wood and Bamboo at the loading rate of 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min., in acidic conditions, is showed in Figure 4.29. It was observed from the results that, at the lower loading rate, all the specimen behave in similar pattern. However, at the higher loading rate, the axial compressive strength of the wood and bamboo dropped significantly. The different failure pattern and decomposed sample at the acidic condition are presented in Figure 4.29.

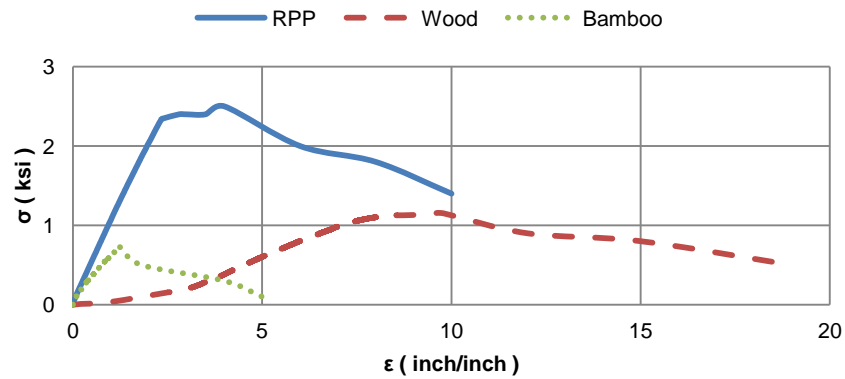
Researchers at the Forest Products Laboratory (FPL) have studied the effect of acid deposition on wood (Williams, 2002). Acid deposition causes more deterioration, even exposed for a short period of time. The behavior of wood , with low peak strength, indicates that the wood has been degraded due to acid submergence and is more prone to fail. The peak strength and modulus of elasticity variations at above mentioned loading rates are shown in Figure 4.31 and Figure 4.32, respectively.



(a)



(b)



(c)

Figure 4.29: Axial variation of stress-strain with different axial rates in Acidic Condition (a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.



(a) Before



(a) After



(b) Before



(b) After



(c) Before



(c) After

Figure 4.30: Comparative diagrams compression in Acidic condition (a) RPP (b) Bamboo (c) Wood



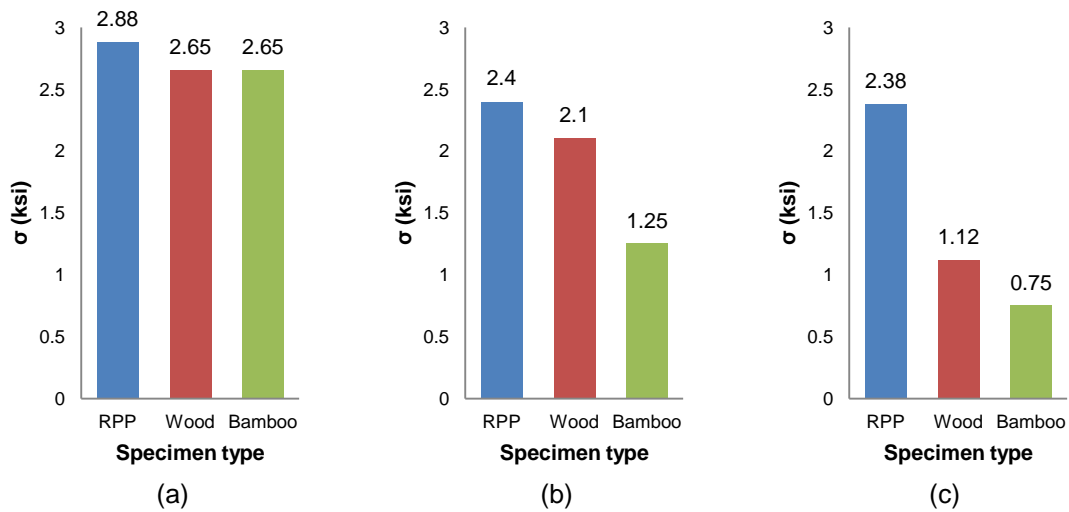


Figure 4.31: Variation of Peak strength with different loading rates in Acidic condition (a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.

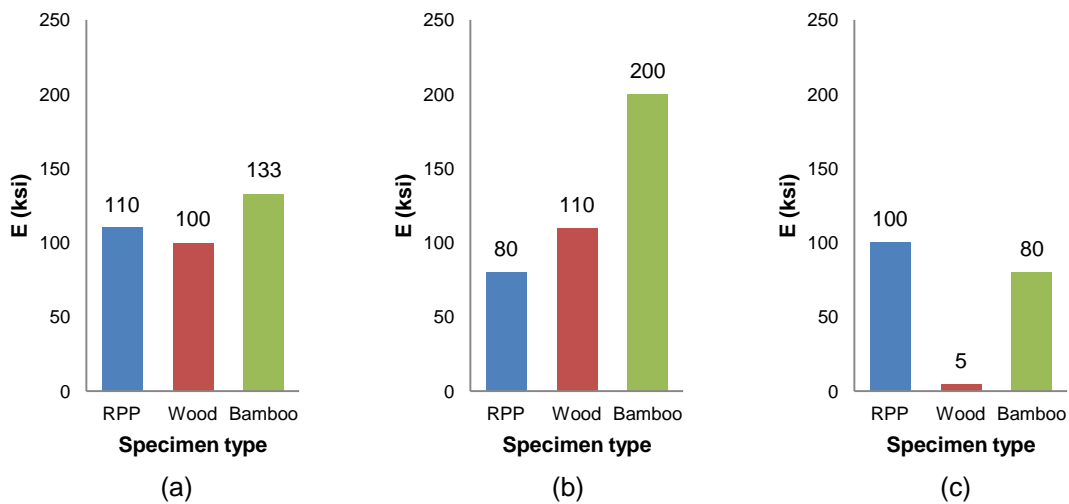


Figure 4.32: Variation of Modulus of Elasticity with different loading rates in Acidic condition (a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.

It was observed that, in acidic conditions, RPP showed higher axial compressive strength compared to wood and bamboo. The variation in modulus of elasticity of RPP, wood and bamboo showed that RPP and wood was almost equal for the loading rate of 2.5 kips/min. and 3.1 kips/min. However, wood experienced significant drop in the axial compressive strength at the loading rate 3.75 kips/min. Bamboo showed stiffer behavior at the 2.5 kips/min. and 3.1 kips/min

compared to RPP. No significant variation of the RPP was observed at the acidic environment with the variation of loading.

Based on the axial compression test, the major findings at the acidic environment for the RPP, wood and bamboo can be summarized below.

- RPP shows higher peak strength in all conditions.
- Wood is more ductile in acidic conditions.
- Bamboo exhibited more erratic behavior in different loading rates.
- The modulus of elasticity of wood has fallen sharply due to degradation.
- The modulus of elasticity of RPP is fairly constant in all rates.

#### 4.3.2.2 At pH = 7.0 solution

For simulating the moist condition with heat, the samples were submerged in a tub filled with water, keeping the top uncovered, in our hot room. The water in it got dried in every one and half week and water was added to keep the condition as desired.

##### 4.3.2.2.1 Behavior of RPP at different axial loading rates

The stress-strain effect of RPP at the loading rate of 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min., in neutral conditions, is shown in Figure 4.33. The failure strain at loading rate at 2.5 kips/min., 3.5 kips/min. and 3.75 kips/min. is 16%, 3% and 7% respectively. The peak compressive strength and modulus of elasticity variations are presented in Figure 4.34.

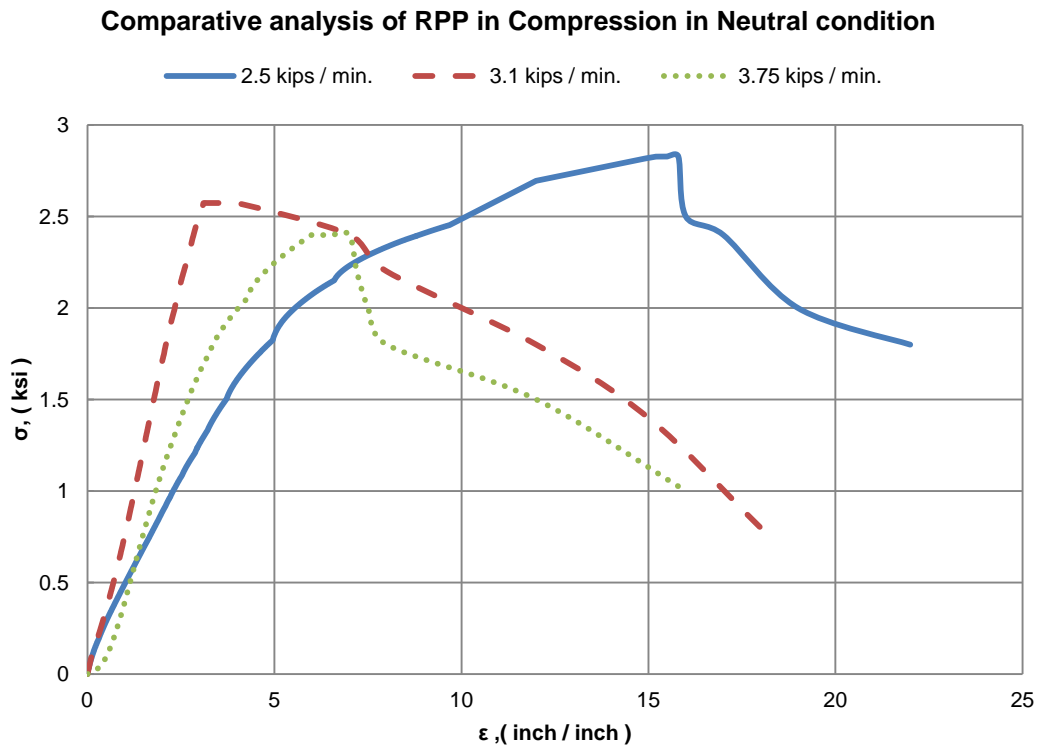
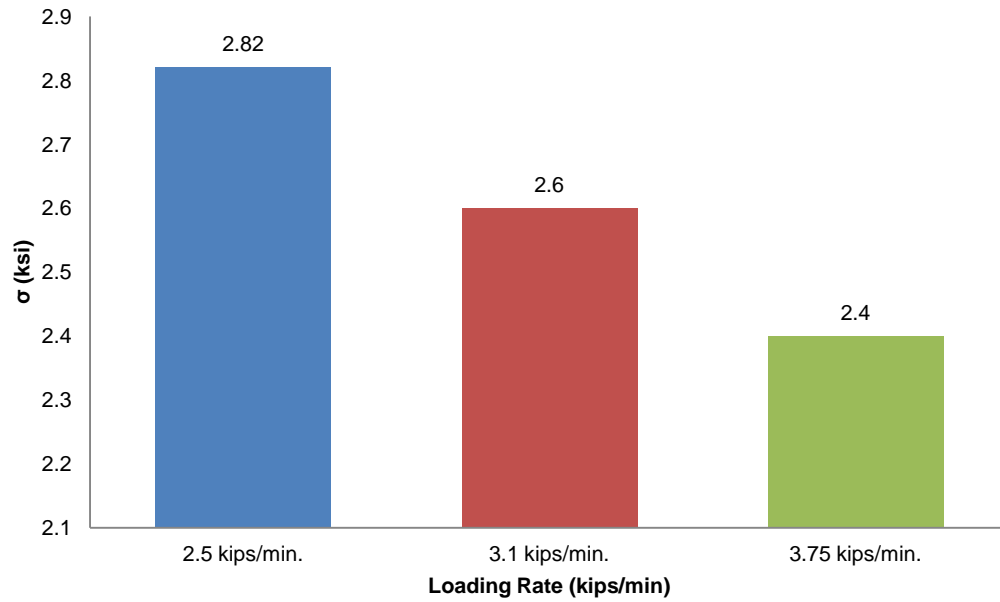
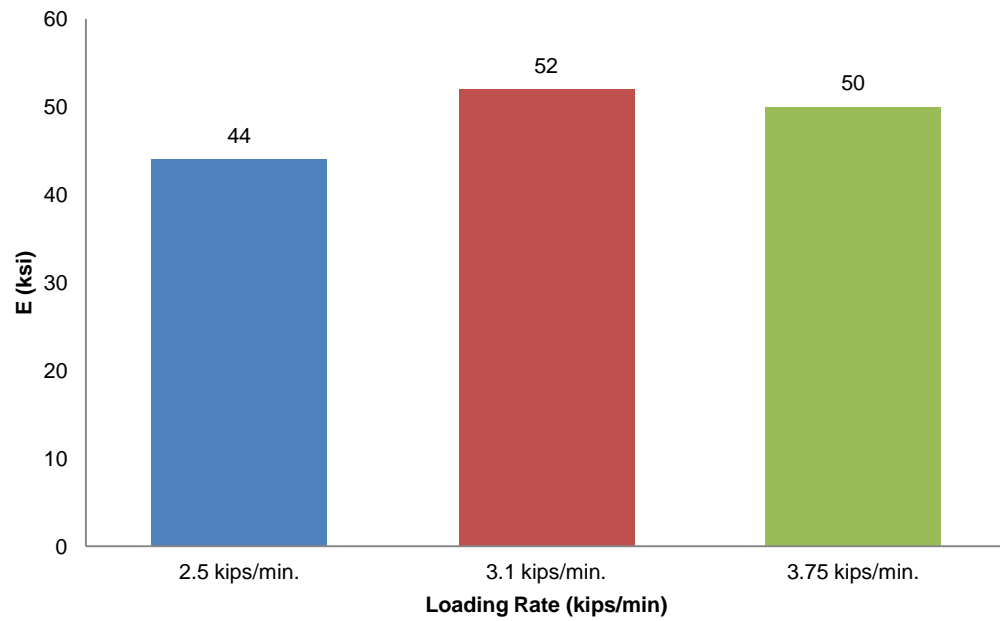


Figure 4.33: Stress-Strain response of RPP at different loading rates in Neutral condition



(a)



(b)

Figure 4.34: Axial Strength variation with loading rates in Neutral Conditions (a) Peak strength variation (b) Modulus of Elasticity Variation

At the neutral condition, with the increase of the loading rate, the compressive strength of the RPP goes down. In addition no significant variation of modulus of elasticity was observed with the increased loading rate for the RPP.

#### 4.3.2.2.2 Behavior of Wood at different axial loading rates

The stress-strain effect of wood at the loading rate 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min., in neutral conditions, is shown in Figure 4.35. From the stress strain behavior of the wood sample submerged at the neutral condition, the failure strain was in between 2-3% for all the loading rates. The sample had higher compressive strength for the loading rate of 2.5 kip/min. On the other hand, the compressive strength was very close for the loading rate of 3.1 kip/min and 3.75 kip/min. The variation of the peak compressive strength and the modulus of elasticity are shown in Figure 4.36.

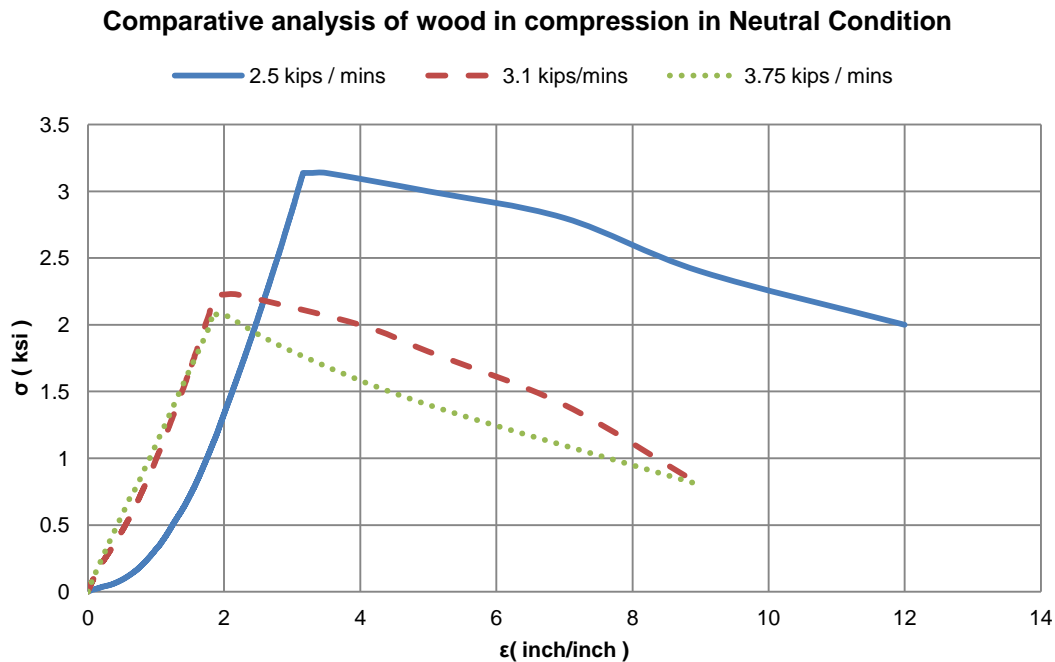
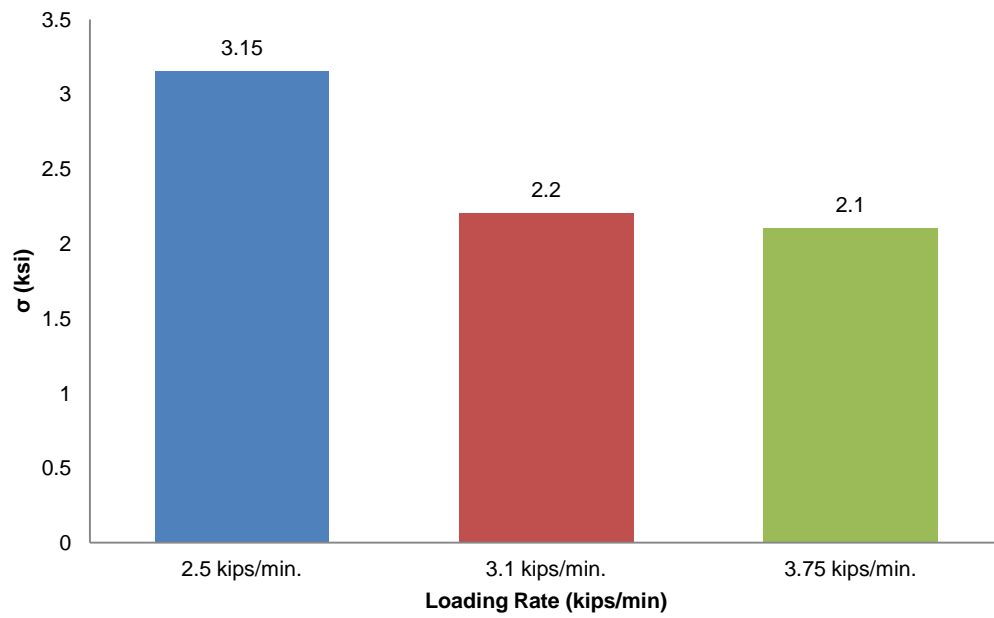
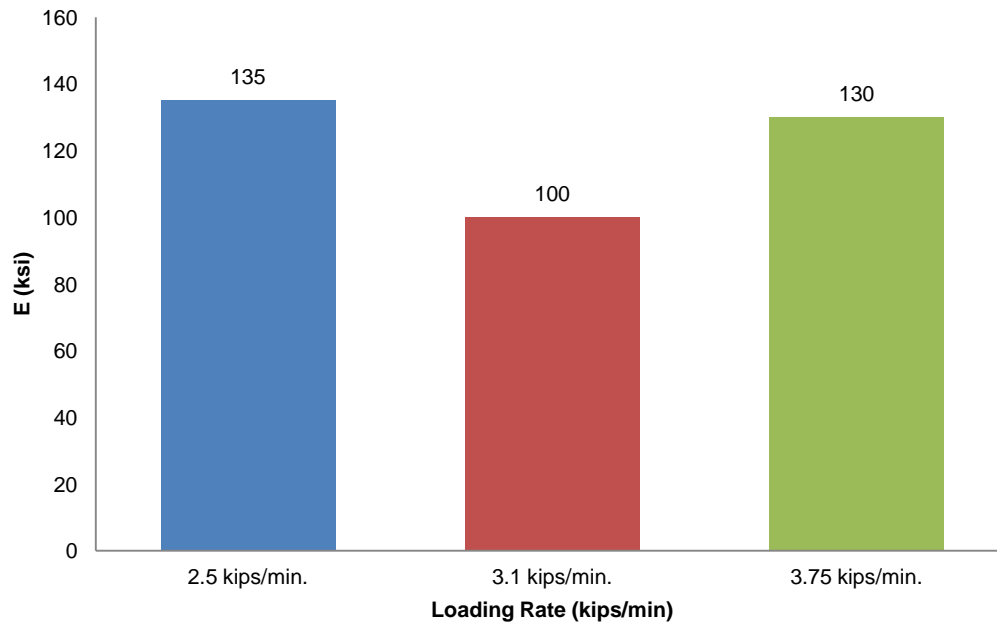


Figure 4.35: Stress-Strain response of Wood at different loading rates in Neutral condition



(a)



(b)

Figure 4.36: Axial Strength variation with loading rates in Neutral Conditions (a) Peak strength variation (b) Modulus of elasticity variation

#### 4.3.2.2.3 Behavior of Bamboo at different axial loading rates

The stress-strain effect of bamboo at the loading rate of 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min., in neutral conditions, is shown in Figure 4.36. It was observed from the stress-strain curve of bamboo specimen in neutral condition that the failure strain at the loading rates of 2.5 kips/min. and 3.5 kips/min. is 2%. However, the compressive strength was observed higher at higher loading rate of 2.5 kip/min. The failure occur at 1% strain for the loading rate of 3.75 kips/min. The peak compressive strength and modulus of elasticity variations at above mentioned loading rates are shown in Figure 4.37.

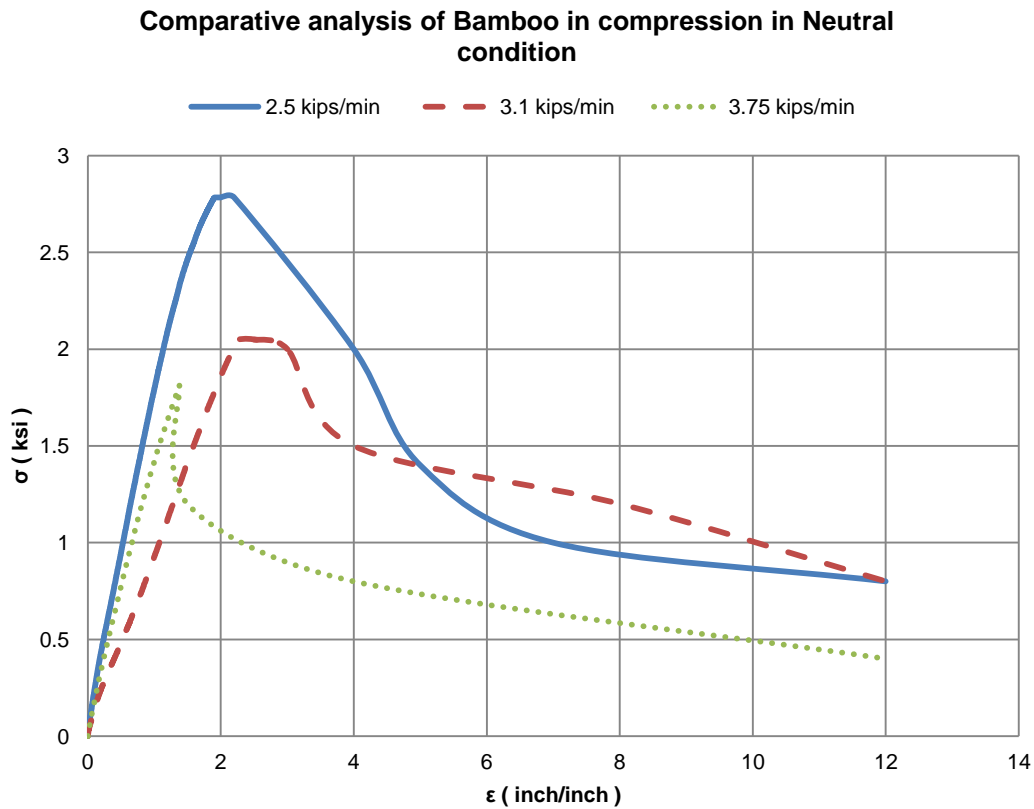
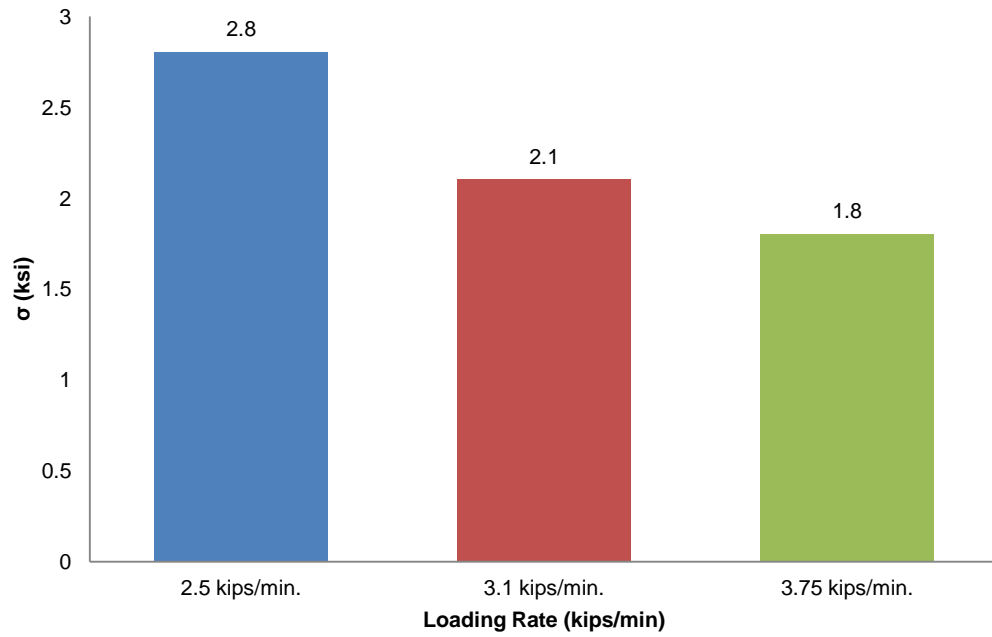
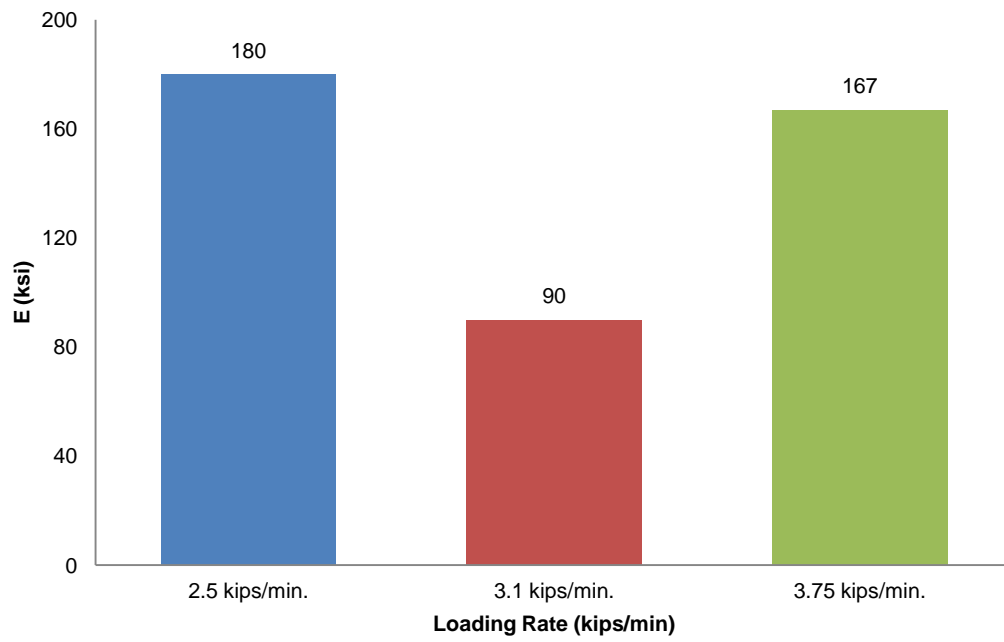


Figure 4.37: Stress-Strain response of Bamboo at different loading rates in Neutral condition



(a)



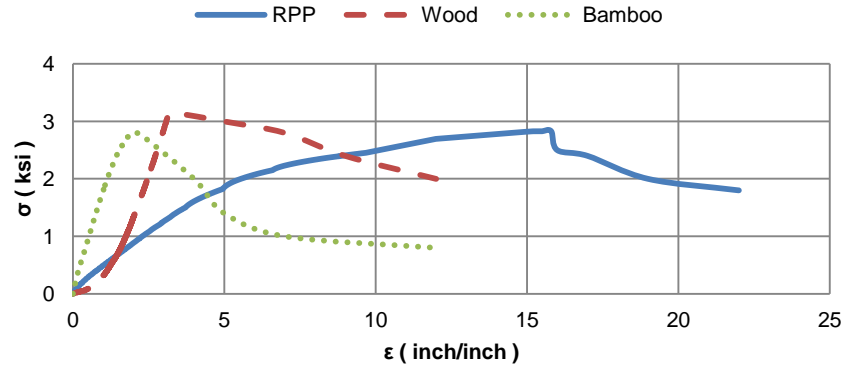
(b)

Figure 4.38: Axial Strength variation with loading rates in Neutral Conditions (a) Peak strength variation (b) Modulus of Elasticity Variation

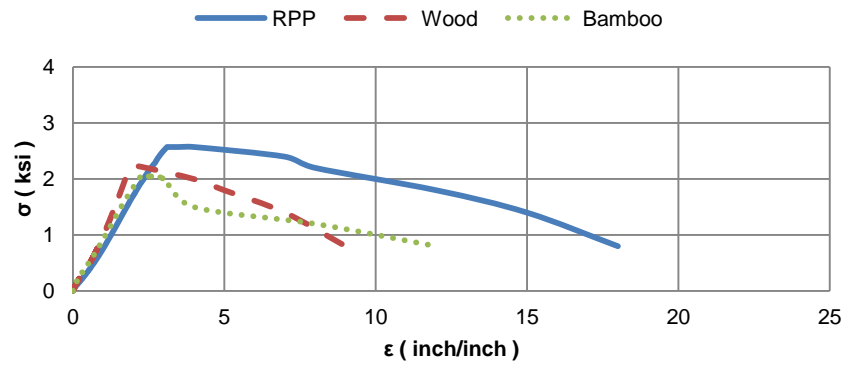


#### 4.3.2.2.4 Comparison of different specimen in neutral conditions at different axial rates

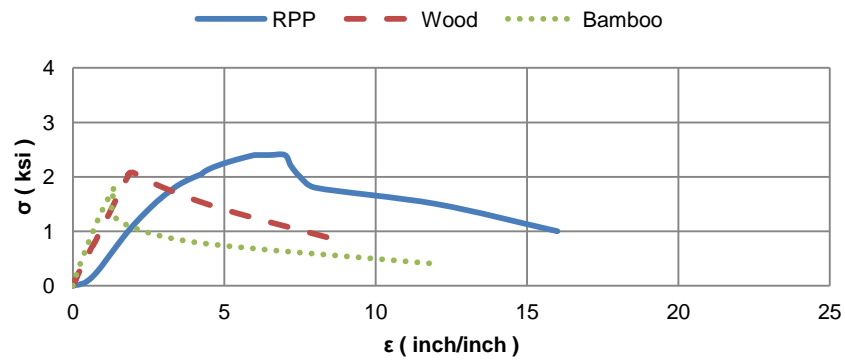
The axial behavior of RPP, Wood and Bamboo at the loading rate of 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min., in neutral conditions, is showed in Figure 4.39. In addition, the photo of the failure mode and the peak strength and modulus of elasticity variations are presented in the Figures 4.40, 4.41 and 4.42, respectively. It was observed that at 2.5 kips/min., wood showed higher peak strength at the loading rate of 3.1 kips/min. and 3.75 kips/min., In addition, the presence of moisture, with heat, has a significant effect on bamboo (Godbole, 1986). It loses its strength and rigidity due to exposed to dry humid weather. Similar trend was observed for wood also. It experiences a strength drop with increasing moisture compared to the strength without any environmental effect.



(a)



(b)



(c)

Figure 4.39: Axial variation of stress-strain with different axial rates in Neutral Condition (a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.



(a) Before



(a) After



(b) Before



(b) After



(c) Before



(c) After

Figure 4.40: Comparative diagrams in compression in Neutral condition (a) RPP (b) Bamboo (c) Wood

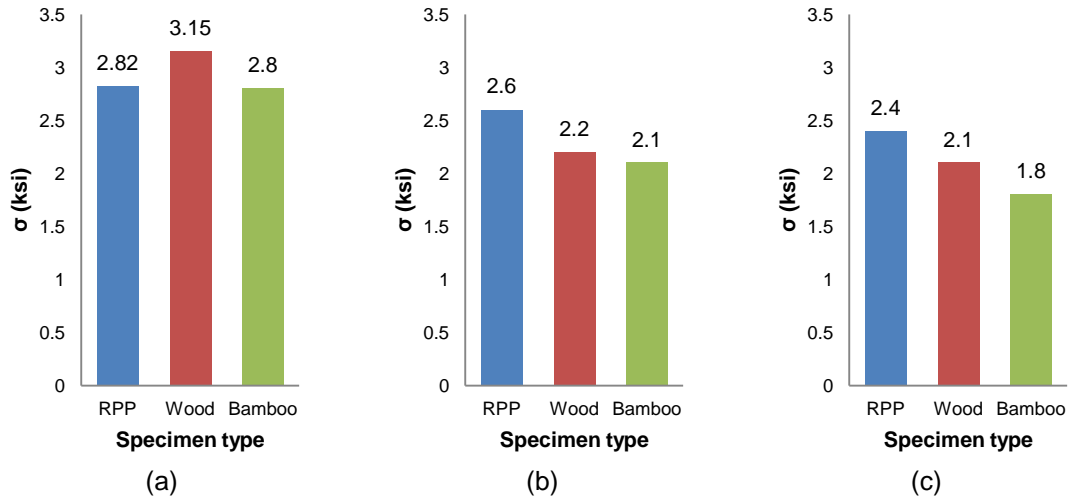


Figure 4.41: Variation of Peak strength with different loading rates in Neutral condition (a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.

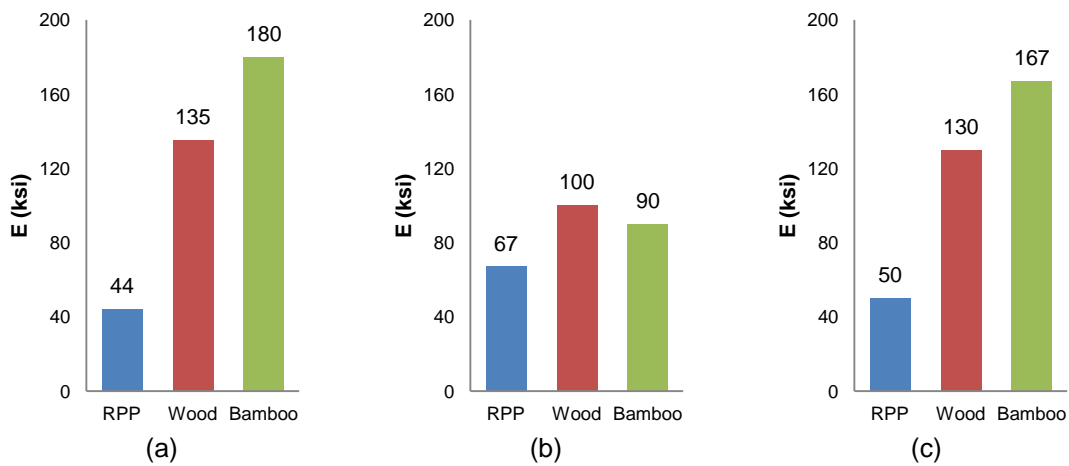


Figure 4.42 : Variation of Modulus of Elasticity with different loading rates in Neutral condition (a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.

Based on laboratory investigation at the neutral condition for the RPP, wood and bamboo, the following conclusions can be made.

- RPP and bamboo shows similar peak strength at the lowest loading rate.
- Wood shows highest peak strength, compared to RPP and bamboo, at the lowest loading rate.
- RPP exhibits highest peak strength in the succeeding loading rates.

- The modulus of elasticity of wood and RPP was fairly constant, as compared to bamboo, in the three loading rates.

#### 4.3.2.3 At pH > 7.0 solution

To simulate the effect of Texas black-clay, comprising of a pH value of 8.5 (Region, 2008), the samples were submerged in KOH solution for two months. Weekly observation was made to check whether there is a drop in pH and corrective measures were taken accordingly.

##### 4.3.2.3.1 Behavior of RPP at different axial loading rates

The stress-strain effect of RPP at the loading rate 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min., in alkaline conditions, is shown in Figure 4.43. The RPP had higher compressive strength for the loading rate of 2.5 kip/min. However, the compressive strength was closer for the loading rate of 3.1 kip/min and 3.75 kip/min. The elastic modulus for compression was observed closer for all the loading condition. The peak strength and modulus of elasticity variations of RPP at the alkaline condition are presented in Figure 4.44.

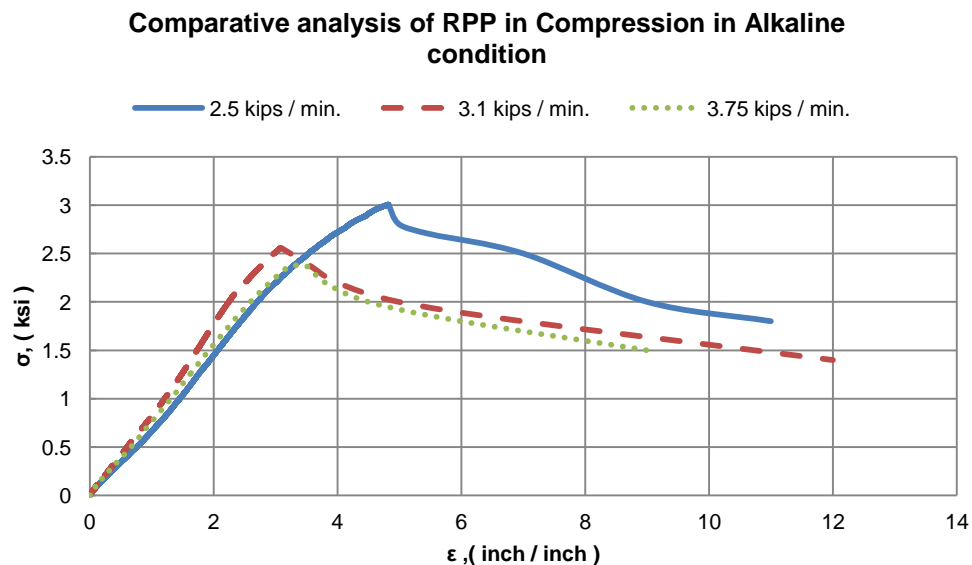
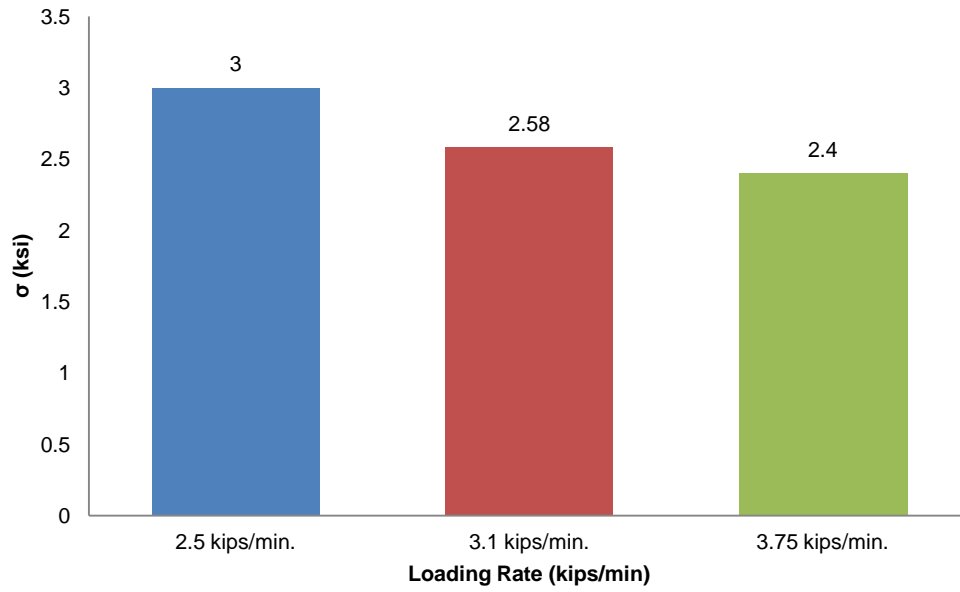
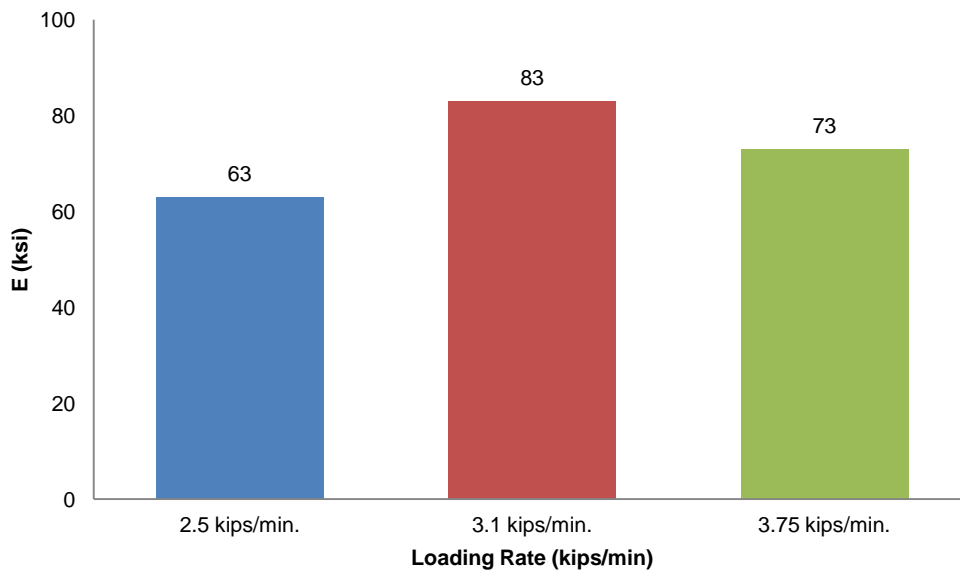


Figure 4.43 : Stress-Strain response of RPP at different loading rates in Alkaline condition



(a)



(b)

Figure 4.44: Axial Strength variation with loading rates in Alkaline Conditions (a) Peak Strength Variation (b) Modulus of Elasticity Variation

The peak compressive strength of RPP decreased with increasing loading rate. However, no significant variation was observed in the elastic modulus of RPP at the alkaline condition.

#### 4.3.2.3.2 Behavior of Wood at different axial loading rates

The stress-strain effect of Wood at the loading rate of 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min., in alkaline conditions, is shown in Figure 4.45. The stress-strain behavior showed similar trends for wood, in compression with alkaline condition. The plastic behavior was more observed for the loading rate of 3.1 kips/min. compared to the other loading rates. The peak strength and modulus of elasticity variations at the alkaline condition for wood samples are presented in Figure 4.46.

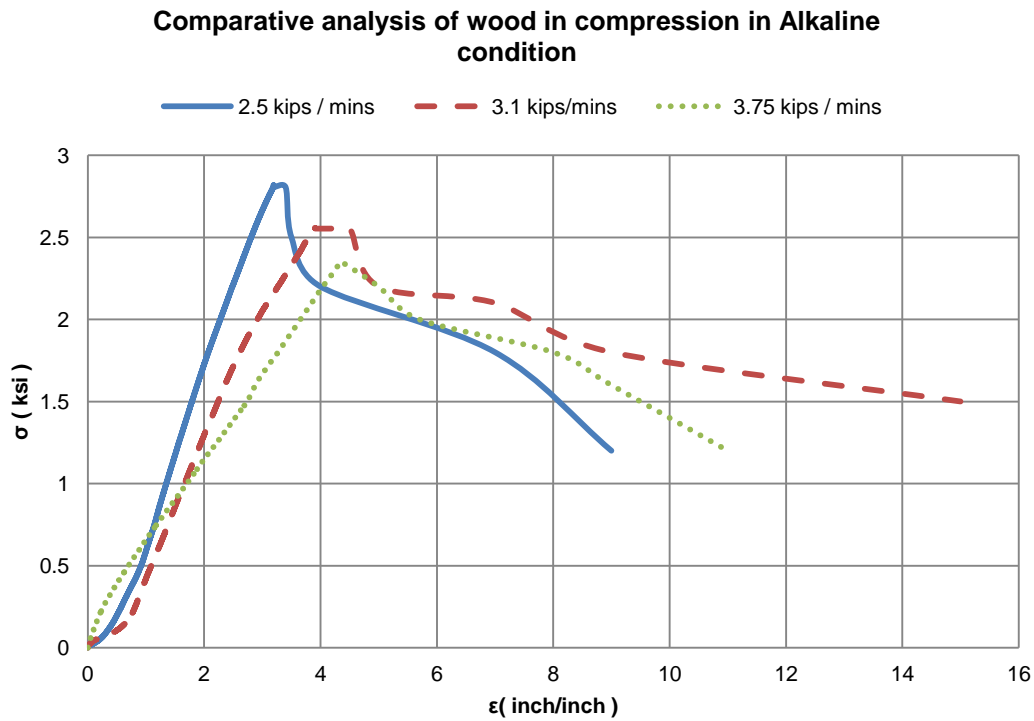
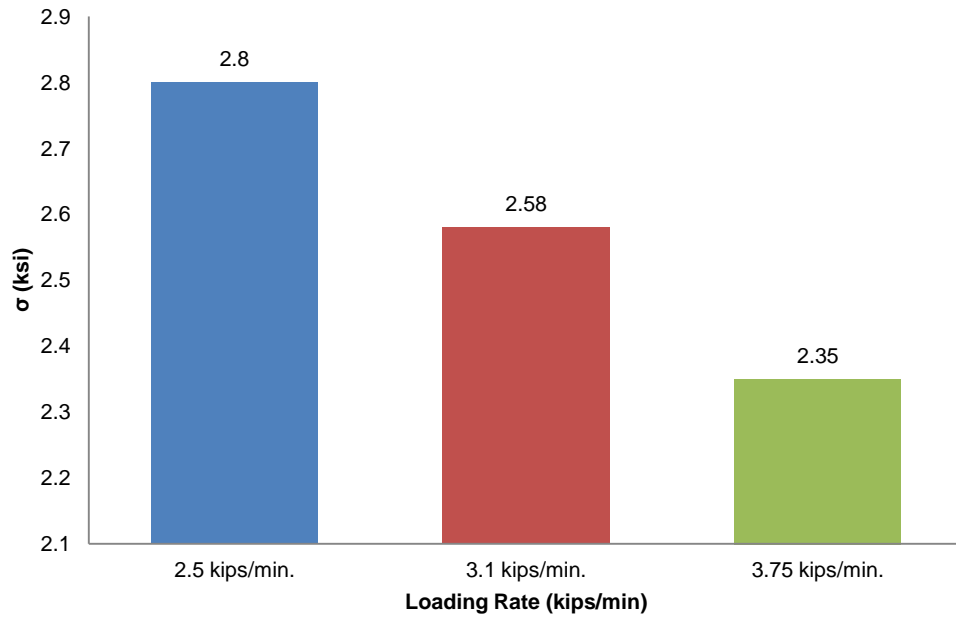
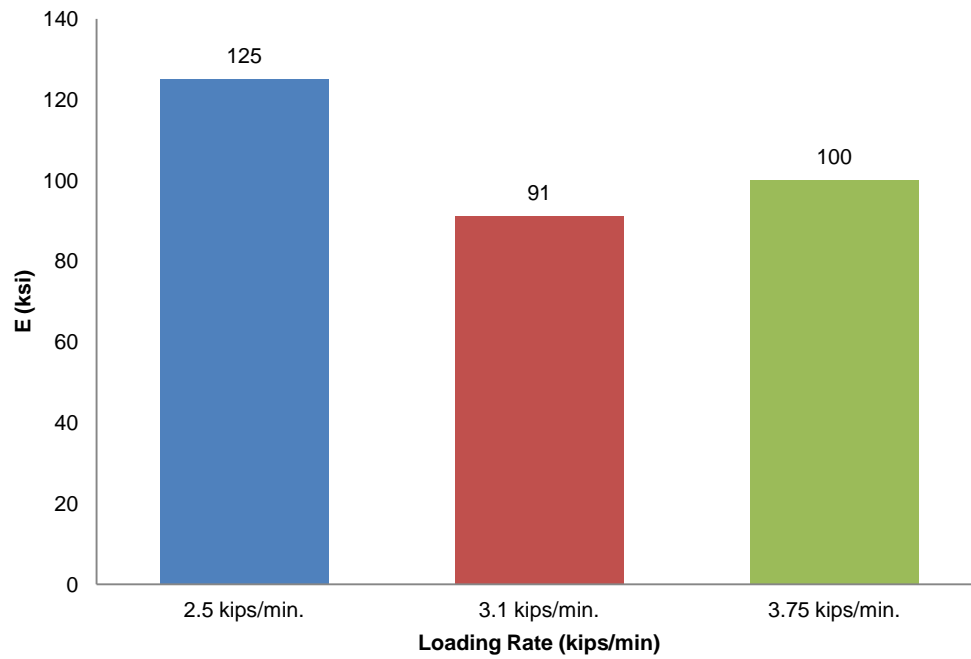


Figure 4.45: Stress-Strain response of Wood at different loading rates in Alkaline condition



(a)



(b)

Figure 4.46: Axial Strength variation with loading rates in Neutral Conditions (a) Peak strength variation (b) Modulus of elasticity variation



#### 4.3.2.3.3 Behavior of Bamboo at different axial loading rates

The stress-strain effect of bamboo at the loading rate of 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min., in alkaline conditions, is shown in Figure 4.47. It was observed that the peak compressive strength of the bamboo decreased with the increase loading rate. The elastic modulus of the bamboo at the alkaline condition was observed closer for the loading rate of the 2.5 kip/min and 3.1 kip/min. However, a decreased in the elastic modulus was observed at the higher rate of loading. The peak strength and modulus of elasticity variations at the alkaline condition for bamboo are presented in Figure 4.48.

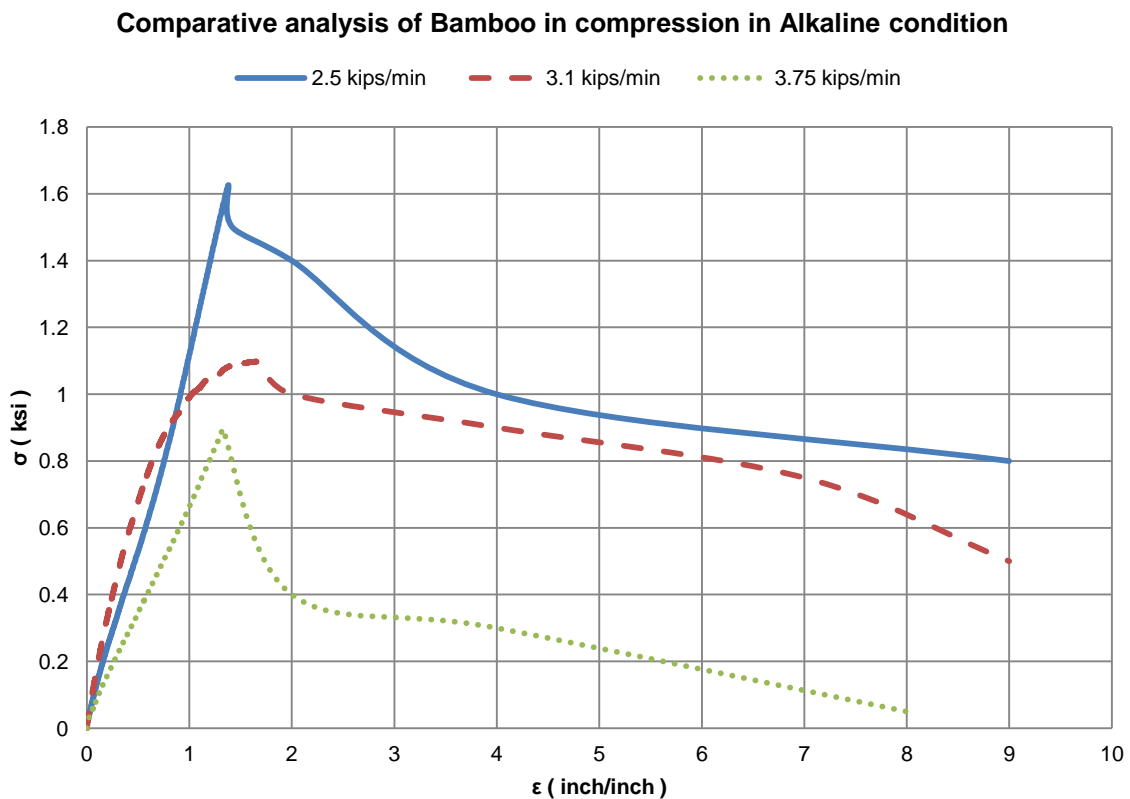
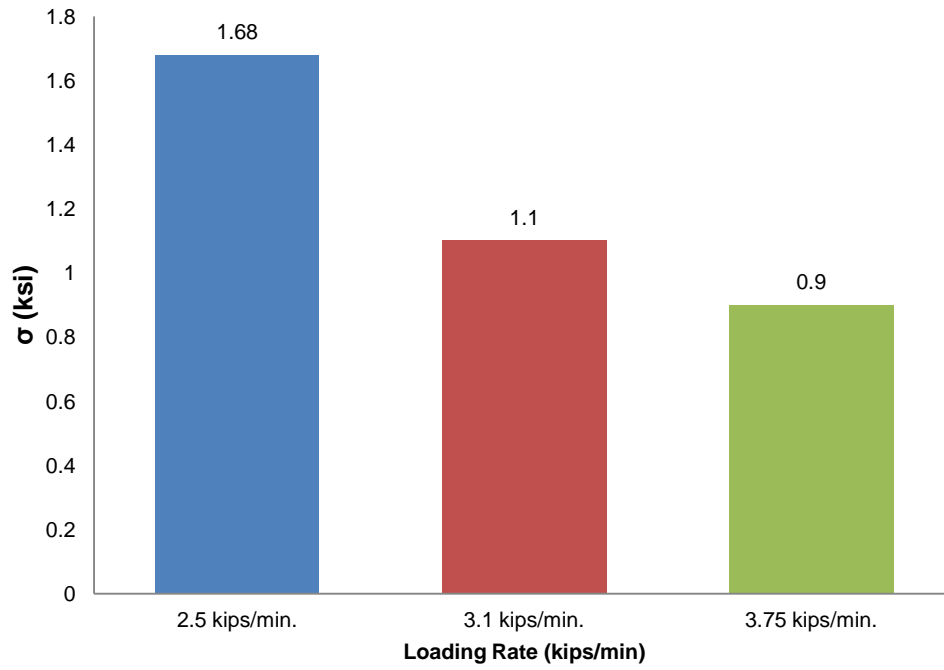
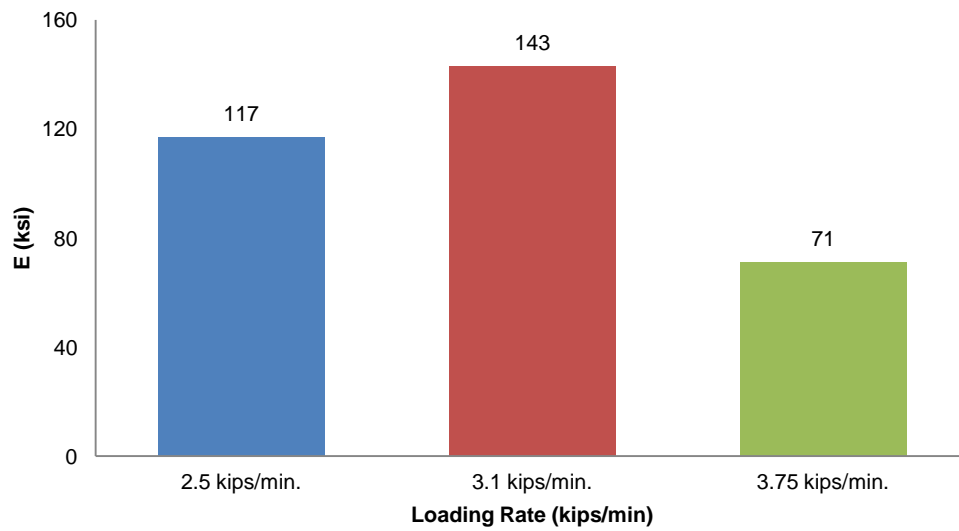


Figure 4.47: Stress-Strain response of Bamboo at different loading rates in Alkaline condition



(a)

**Compressive Modulus of Elasticity variation at different loading rates**

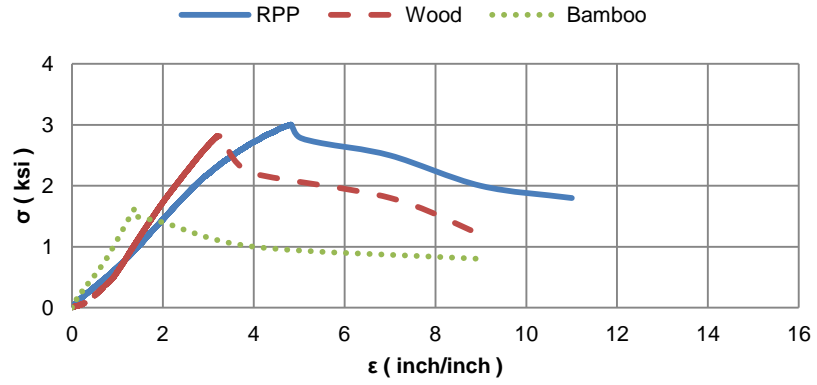


(b)

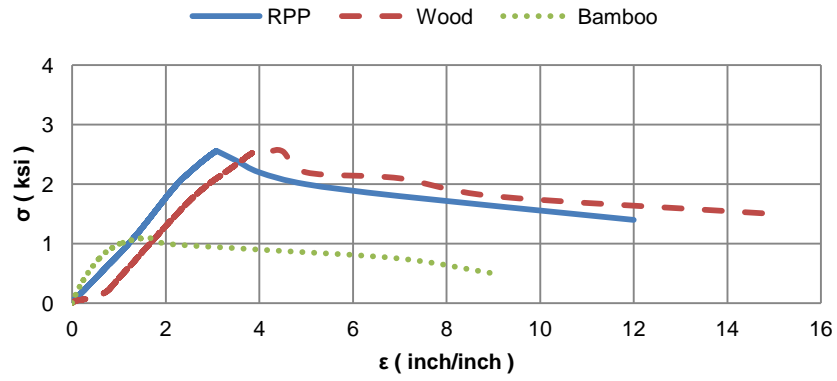
Figure 4.48: Axial Strength variation with loading rates in Alkaline Conditions (a) Peak Strength Variation (b) Modulus of Elasticity Variation

#### 4.3.2.3.4 Comparison of different specimen in Alkaline conditions at different axial rates

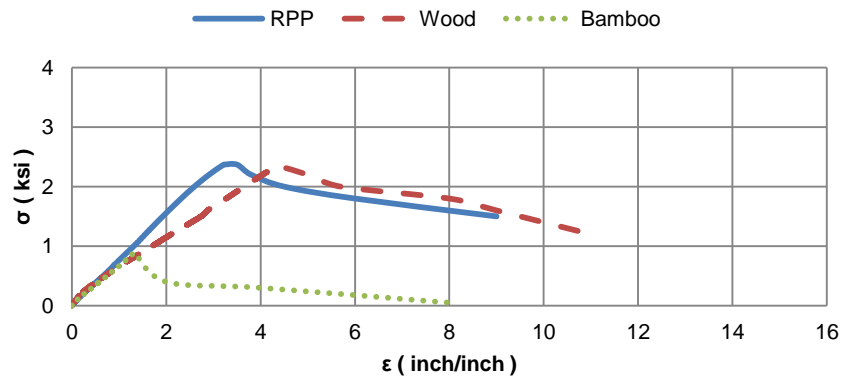
The axial behavior of RPP, Wood and Bamboo at the loading rate of 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min., in alkaline conditions, is showed in Figure 4.49. No significant variation was observed at the stress strain curve for RPP at the alkaline condition compared to the normal condition. However, the peak of the stress strain curve dropped and shifted right for both wood and bamboo which mean, the elastic behavior of wood and bamboo goes down at the alkaline condition. It was found in the literature that alkaline solutions are more destructive than acid conditions to wood (Agriculture, 2007) . Therefore, this result was found to be in good agreement with the previous study in the literature. The comparison of peak compressive strength and elastic modulus of RPP, wood and bamboo are presented in Figure 4.50 and Figure 4.51, respectively.



(a)



(b)



(c)

Figure 4.49: Axial variation of stress-strain with different axial rates in Alkaline Condition  
(a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.

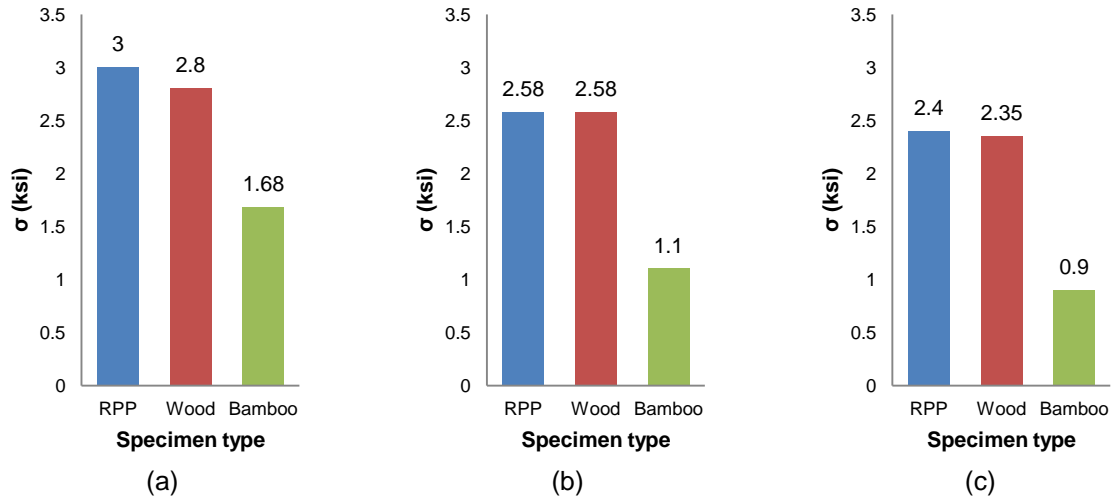


Figure 4.50: Variation of Peak strength with different loading rates in Alkaline condition (a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.

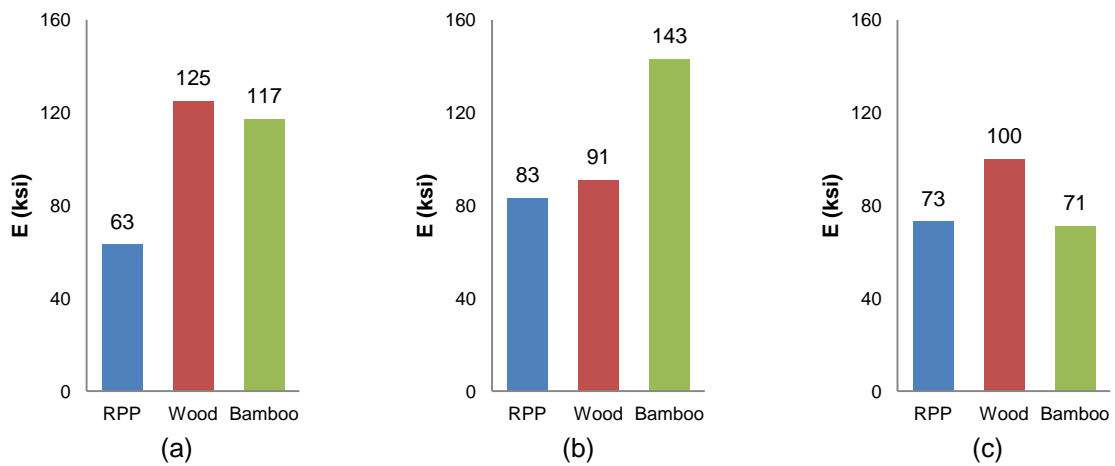


Figure 4.51: Variation of Peak strength with different loading rates in Alkaline condition (a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.

Based on the axial compression test, the major findings at the acidic environment for the RPP, wood and bamboo can be summarized below.

- RPP and wood possess similar peak strength in all conditions
- RPP shows more consistency in the modulus of elasticity than wood and bamboo.

- RPP exhibits more elastic behavior at the lowest loading rate.
- Wood is more ductile at the average and the highest loading rate.
- Bamboo exhibits more mercurial nature compared to wood.

#### 4.3.3 Final Comparison between the specimen at different conditions

The change in engineering properties of RPP, wood and bamboo in different environment conditions, in compression, is discussed in the subsequent sections.

##### 4.3.3.1 RPP

The stress-strain behavior of RPP for the loading rate of 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min. in different conditions are shown in Figure 4.52. In addition, the peak strength and modulus of elasticity variations at above mentioned loading rates in four environmental conditions are shown in Figure 4.53 and Figure 4.54, respectively. It is observed that RPP shows more consistent values in peak strength in different environmental condition. Regardless of the environmental condition, no significant change in the peak strength and the elastic modulus was observed from the laboratory investigation. Moreover, the peak of the stress strain curve shifted at the left for different environmental condition with different loading rate which signify that at the adverse environmental condition, the elastic modulus of the plastic pin increased. Therefore, based on the uni-axial compression test, it can be concluded that, the plastic pin had no adverse effect on performance due to the environmental condition.

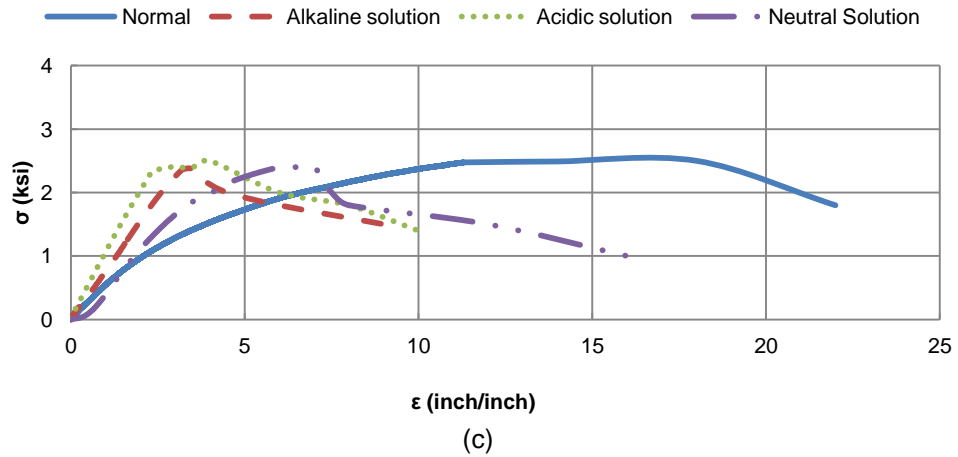
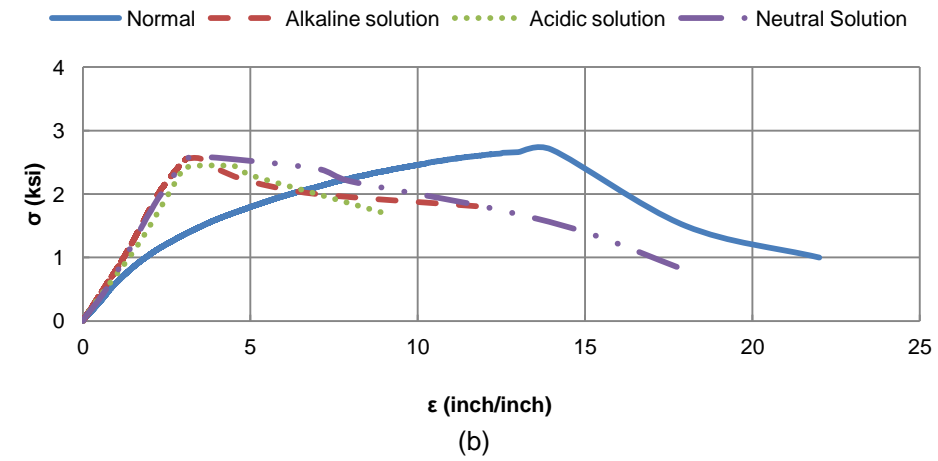
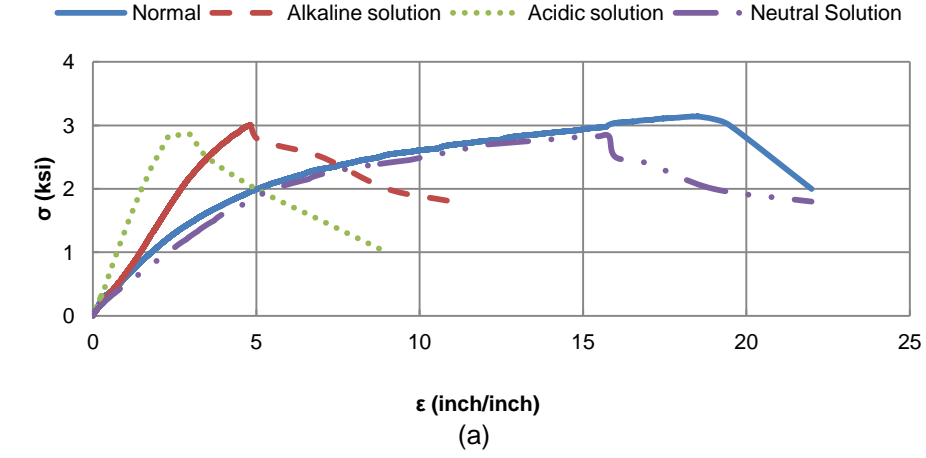
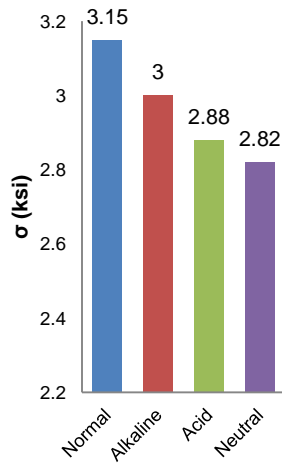
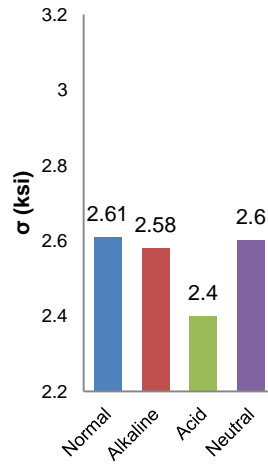


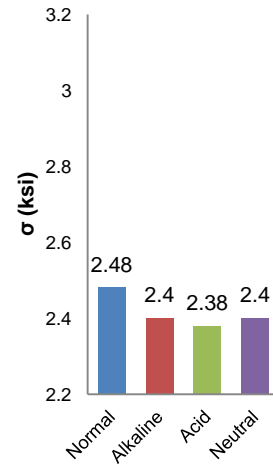
Figure 4.52: Axial behavior of RPP at different conditions at (a) 2.5 kips/min (b) 3.1 kips/min (c) 3.75 kips/min



(a)

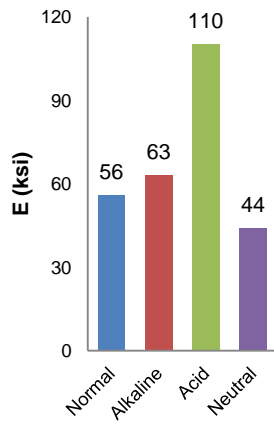


(b)

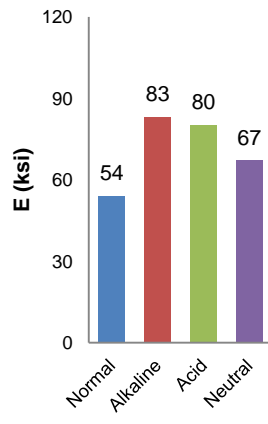


(c)

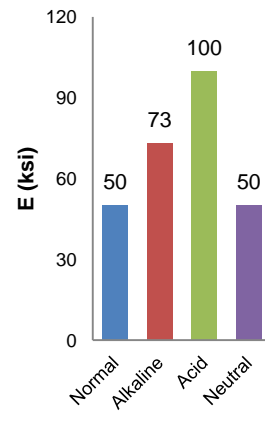
Figure 4.53: Peak Strength variation of RPP with environment conditions at (a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.



(a)



(b)



(c)

Figure 4.54: Modulus of Elasticity variation of RPP with environment conditions at (a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.



#### 4.3.3.2 Wood

The stress-strain behavior of wood with different loading rate of 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min. in different environmental conditions are shown in Figure 4.55. In addition, the peak strength and modulus of elasticity variations at above mentioned loading rates are shown in Figure 4.56 and Figure 4.57, respectively. It is observed that wood fails to perform as the environment effect is imposed on it. The wood sample during this study was used is pressure-treated and designed to be anti-fungi. However, it was not strong enough to survive in the environment conditions. The peak of the stress strain curve of wood dropped with imposed environmental condition as presented in Figure 4.55 which signify the compressive strength of wood affected with the environmental condition as presented in Figure 4.56. Therefore, it can be concluded that, the environmental condition had adverse effect on the performance of the wood lumber.

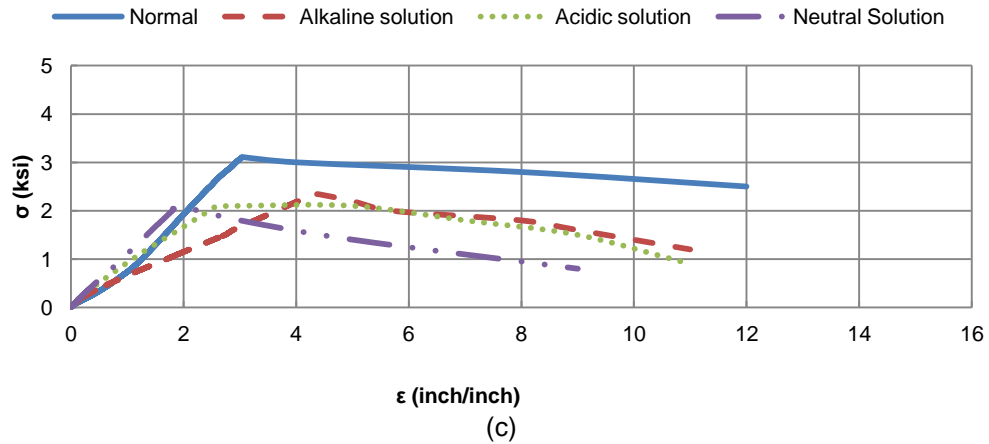
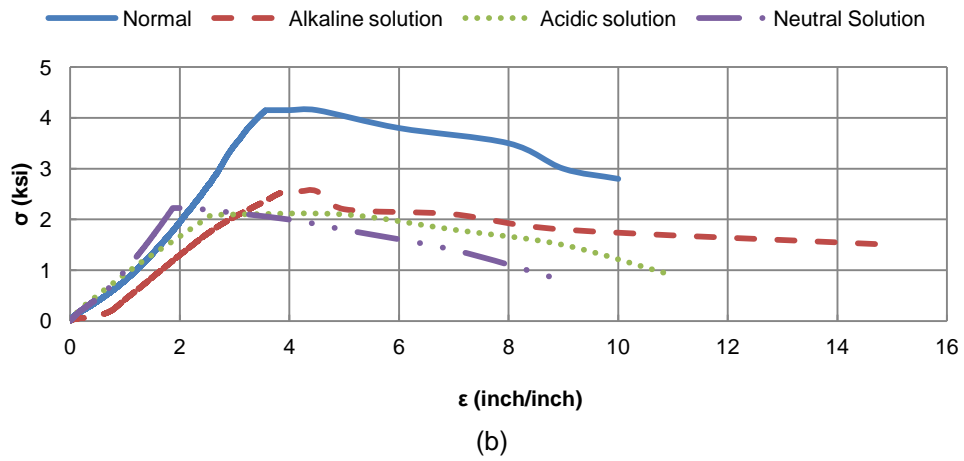
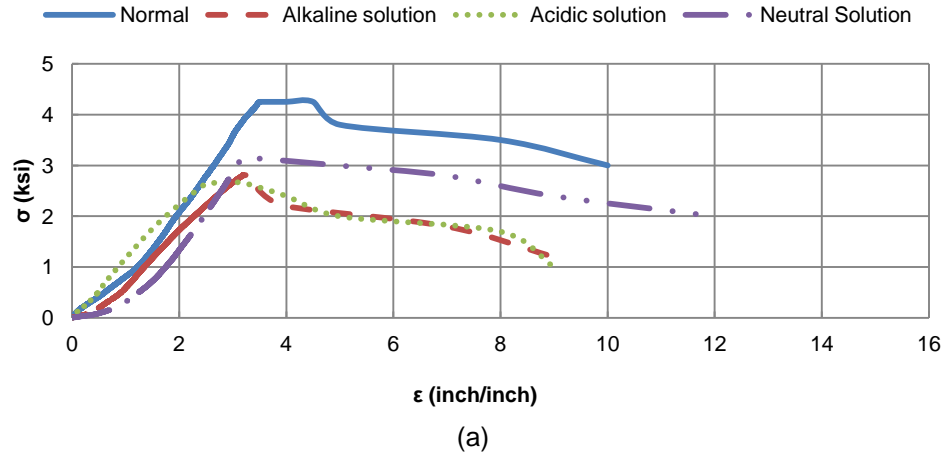


Figure 4.55: Axial behavior of Wood at different conditions at (a) 2.5 kips/min (b) 3.1 kips/min (c) 3.75 kips/min.

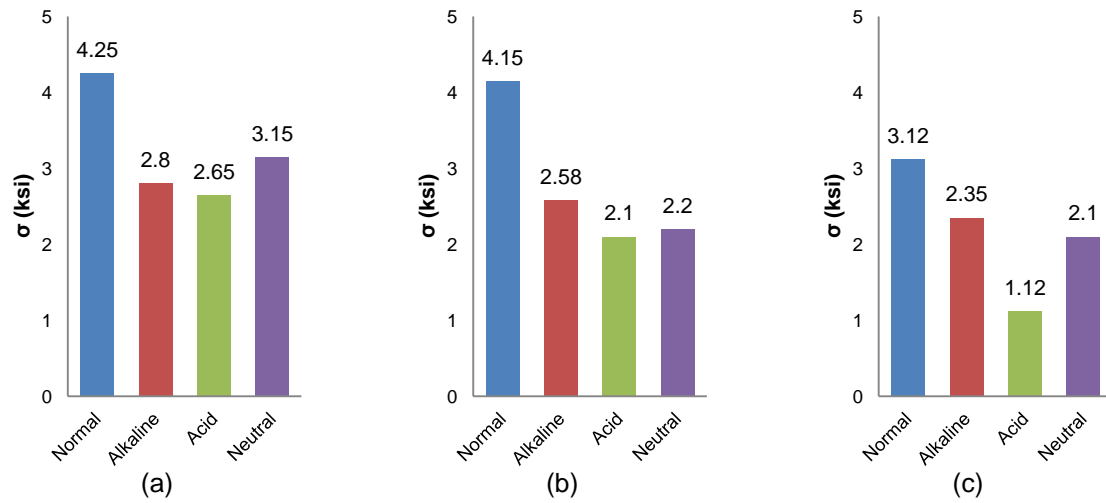


Figure 4.56: Peak Strength variation of Wood with environment conditions at (a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.

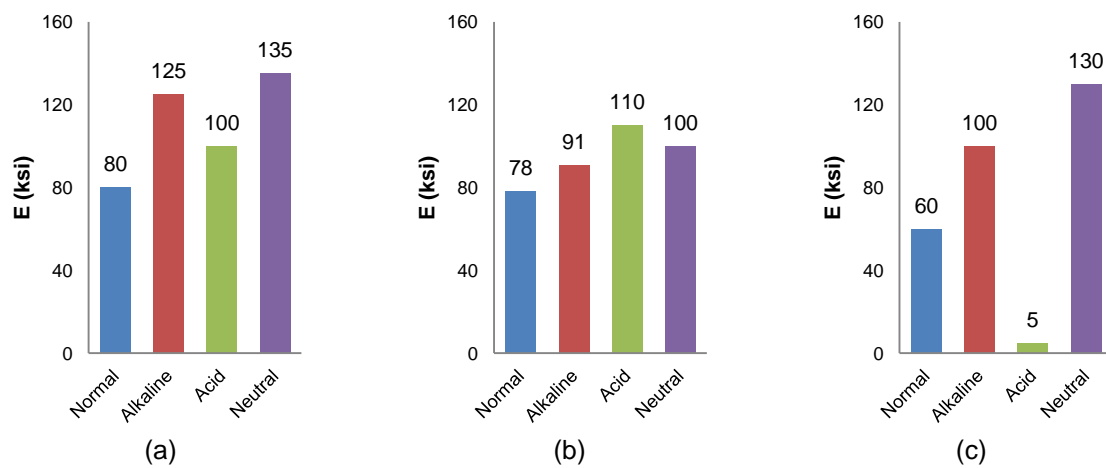


Figure 4.57: Modulus of Elasticity variation of Wood with environment conditions at (a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.

#### 4.3.3.3 Bamboo

The stress-strain behavior of bamboo for the loading rate 2.5 kips/min., 3.1 kips/min. and 3.75 kips/min. in different environmental conditions is shown in Figure 4.58. In addition, the peak strength and modulus of elasticity variations at above mentioned loading rates are shown in Figure 4.59 and Figure 5.60, respectively. It can be mentioned that, the similar behavior was observed for bamboo compared to the wood lumber for the different environmental condition. The stress strain curve dropped down with different environmental condition as presented in Figure 4.58. In addition, the variation of the modulus of elasticity was observed erratic with different environmental condition. The erratic behavior of bamboo may takes place due to natural anisotropy and position of the knots.

Bamboo is used extensively in under-developed countries, most likely to the south and south-east Asian parts in a variety of engineering applications - in the sense of being major load-bearing elements. At the peak rate of 3.75 kips/min., the modulus of elasticity of bamboo was almost equal at normal and neutral conditions, being 167 ksi. It might indicate bamboo performs good in high loading conditions and moist environment. Bamboo is the world's fastest growing plant and some species of bamboo can grow up to a foot a day, if nurtured in the right conditions. Bamboo offers excellent engineering properties, with specific strength and modulus, as compared to that of unidirectional glass-reinforced plastics (Lakkd and Godbole, 1986). Based on the laboratory investigation, the bamboo poles affected with the environmental condition. However, a detailed investigation is recommended to verify it's applicability for the slope stabilization.

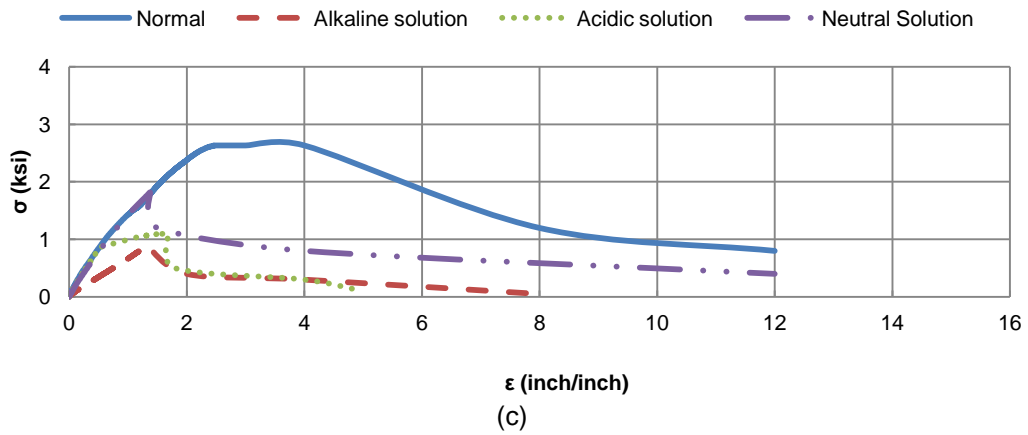
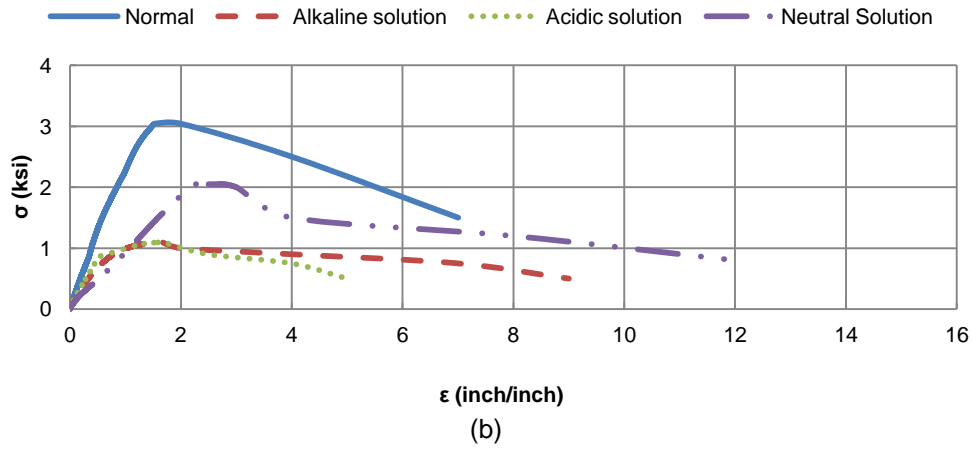
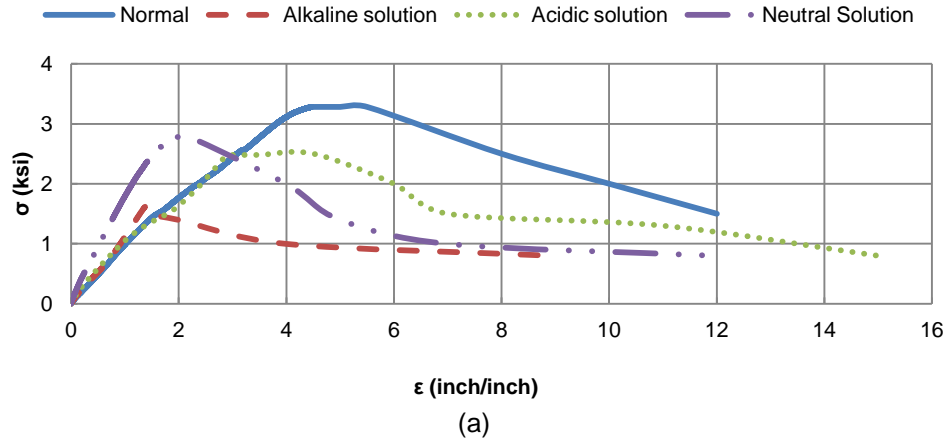


Figure 4.58: Axial behavior of Bamboo at different conditions at (a) 2.5 kips/min (b) 3.1 kips/min (c) 3.75 kips/min

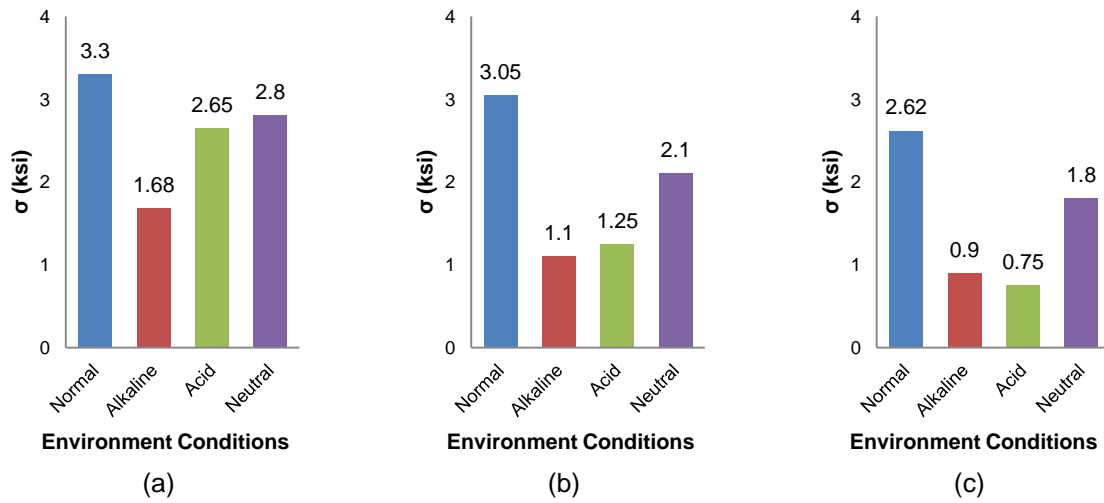


Figure 4.59: Peak Strength variation of Bamboo with environment conditions at (a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.

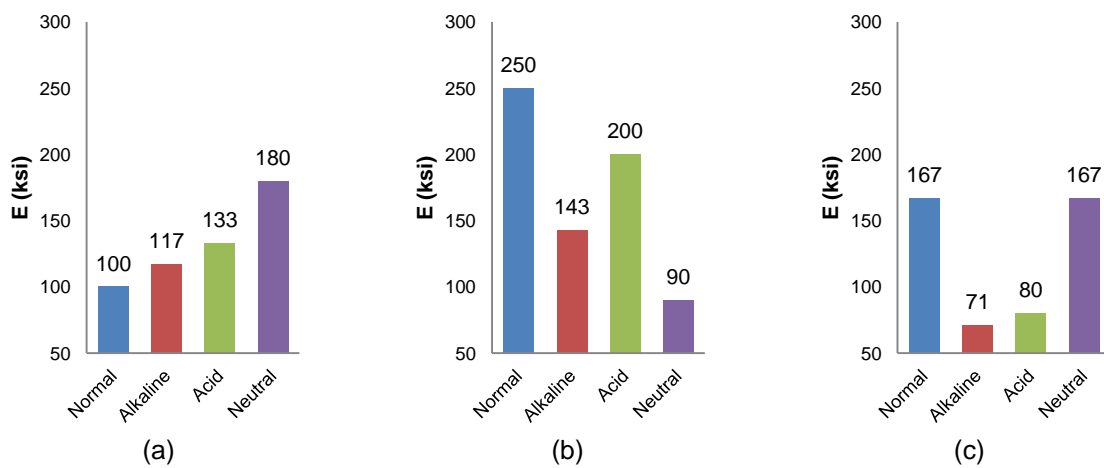


Figure 4.60: Modulus of Elasticity variation of Bamboo with environment conditions at (a) 2.5 kips/min. (b) 3.1 kips/min. (c) 3.75 kips/min.

## CHAPTER 5

### CONCLUSION AND RECOMMENDATION

The objective of this study was to conduct a comparative investigation for Recycled plastic lumber, Wood and Bamboo, and to recommend a feasible and environment friendly solution to mitigate slope instability. Wood and bamboo are locally available material, as compared to RPP which comparatively new and yet to be implemented in many parts of USA. However, it is important to have clear knowledge of these materials to match with the locally used conditions. The current study is focused on the axial and flexure properties of these materials. To simulate the effect of environment degradation on the samples, they were kept in a controlled environment for two months to have an idea as how they will behave in the field conditions.

#### 5.1 Summary and Conclusions

The result of the work performed can be summarized as follows:

1. In flexure, each specimen were subjected to three different rates and for each rate, three samples of each specimen and for each rate were tested. Based on the experimental results it was observed that Recycled plastic lumbers are more elastic, as compared to wood and bamboo.
2. The rates applied in flexure were based on the ASTM standards. Within this range, wood showed higher peak strength than its counterparts. It was observed with the increase of loading rates; all three specimens experienced a fall in peak strength, consecutively. It implies the same materials will bear differently with different movement of soil.
3. The flexural modulus of elasticity for RPP was consistent in all three rates, as compared to wood and bamboo. This was expected as the material was pre-fabricated and the properties were controlled during manufacturing process. Wood and bamboo exhibited

4. Natural anisotropy that reflected in their flexural modulus values. In flexure, it was further observed that after a certain limiting strain, wood and bamboo failed whereas RPP continued to accommodate more strains. In case of wood, it was 0.38%, 0.42% and 0.25 % for the rates of 0.5 kips/min., 2.7 kips/min. and 4.9 kips/min., respectively. For bamboo, it was 0.5%, 0.6% and 0.38 %, respectively for the above mentioned rates. In case of RPP, it was 2%, 1.4% and 0.8%, respectively for the three mentioned rates. It may imply that RPP can be used to inhibit large soil movements and might be more impelled against slope instability.
5. For shallow slope failures, wood and bamboo might be preferred over RPP, provided the strain and the loading effect is within the above mentioned range for them, respectively.
6. In axial compression, each specimen were subjected to three different rates and for each rate, three samples of each specimen and for each rate were tested. For environment conditions, the samples were submerged in acidic, basic and neutral solutions to simulate the soil and weather conditions in Texas, for two months. Without environment degradation, wood shows higher peak strength in all loading rates, as compared to RPP and bamboo.
7. The result trend was similar as that of flexure test results with wood and bamboo failed after certain limiting strain and their modulus of elasticity values was more inconsistent as that of RPP. In case of RPP, it continues up to almost 19% of strain at 2.5 kips/min. with almost 12% of strain at the peak rate of 3.75 kips/min. It might imply that by observing the axial results, we might have an idea of the nature of the materials behavior in flexure. The rates that were applied to test were based on field application rates (Loehr and Bowders, 2007).
8. In acidic conditions, it was observed that after two months of submergence, wood losses its peak strength, compared to RPP, and fails more rapidly at high load rates. Acid deposition in wood causes more deterioration, even exposed for a short period of time (Williams, 2002). A sharp fall in the modulus of elasticity of wood in acidic conditions was



observed as falling to a lowest of 5 ksi at the peak rate of 3.75 kips/min, which previously was 60 ksi, under the same rate and without any degradation effects.

9. Bamboo experienced a similar loss with respect to peak strength and modulus of elasticity values in acidic conditions, as compared to no degradation effects. The peak strength decreased from 2.62 ksi to 0.75 ksi and the modulus of elasticity decreased from 167 to 80 ksi, in the peak loading rate of 3.75 kips/min.
10. In neutral conditions, it was observed that RPP shows more elasticity prior failure, as that of wood and bamboo. Initially, at the low rate of 2.5 kips/min., wood showed higher peak strength. But as the rate continued, RPP gains higher strength than wood and bamboo. It was due to the fact that wood loses its axial strength as the moisture content increases (Cambridge, 2004).
11. Bamboo, in neutral conditions, performed fairly well as the peak strength was equal to that of RPP at the lowest rate and equal to wood at the subsequent rates. The peak strength in 3.75 kips/min decreased from the no degraded condition of 2.62 ksi to a neutral condition of 1.8 ksi where wood experienced 3.12 ksi to 2.1 ksi at similar conditions. However, decrease in strength in RPP was from 2.48 ksi to 2.4 ksi, at the same rate.
12. In alkaline conditions, it was observed that wood and RPP exhibited almost similar strength in all conditions. In case of modulus of elasticity values, RPP was more consistent in all the rates whereas wood was more erratic. The decrease in strength for wood was significant, from 2.62 ksi to 0.9 ksi, considering no degradation and alkaline conditions at the same peak rate of 3.75 kips/min, respectively.
13. Considering everything, the flexible nature of three materials were affected by the environment conditions but if we observe the stress-strain curves for the three individual specimens in all conditions, it will be noticed that the performance of wood and bamboo was susceptible to environment conditions and it will continue to degrade more if the samples were submerged further, as the case will be in reality.

14. In case of RPP, the peak strength at 3.75 kips/min., the variation was seen to be the highest value in no degraded conditions to be 2.48 ksi with the lowest to be 2.38 ksi in acidic conditions.
15. The different loading rates applied in axial compression represents the vertical component of the inclined soil load on the specimen. It might imply that depending upon the failure conditions, RPP will offer a more defiant solution to worse soil movements.
16. Finally, it can be concluded that Recycled Plastic Pin will be more matched to in situ conditions to mitigate slope failure.

### 5.2 Recommendations for Future Study

To be more consistent and decisive on the results obtained from the study, it can be recommended that the present work can be further supplemented as mentioned below

1. Environment conditions were performed on axial tests only. It is recommended that flexural tests be also performed on similar conditions to have a better understanding on the behavior of the specimens.
2. The rates applied in flexure were based on ASTM standards. It is recommended that the strain rates can be determined based on in situ failure conditions and based on the data, a clear knowledge on the design peak strength of the specimens can be obtained.
3. The pH value taken for the Texas red clay and black clay was based on more typical values. In case of applying to a particular site, a detailed study can be initially performed to obtain the pH data of the in situ soil and also the moisture content.
4. The environment conditions were prevailed for two months. Therefore the time period of environmental submergence can be extended to be more explicit in decision.
5. In case of environment, only pH value was considered to be the controlling factor in degradation. It can be more site specific if a field study of the in situ prevailing conditions be performed to contemplate as which other factors, for example: Freeze-thaw cycles, might contribute to its service condition.

6. Effects of natural anisotropy, for example: different bamboo pole dia., on the strength can be analyzed further.
7. Co-relation can be developed based on the natural anisotropy, different lumber size and environment considerations with the peak strength.
8. The flexural test performed in the study was the three-point bending test. A four-point bending test can also be performed to have selected range across the length where the sample will experience maximum strength.
9. RPP can be manufactured in compression molded or, extruded. This effect can also be incorporated in analyzing flexural behavior and peak strength.
10. Creep compliance, associated with various environment degradation conditions, can be performed.

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Faisal Shakib Ahmed was born in Dhaka, Bangladesh on November 1, 1982. He has completed his Bachelor of Science in Civil Engineering from Bangladesh University of Engineering and Technology in June, 2007. He started his career as a Junior Engineer in Vitti Sthapati Brindo Ltd., an architectural consulting firm and was involved in different development projects including Asian University for Women in Chittagong, from July 2007 to December 2007. Later, he served as a Project Engineer in Builtform Engineers and Associates from January 2008 to February 2009. Currently, he is serving as a full-time Faculty (On-Leave) in The Department of Civil Engineering in Stamford University Bangladesh. He has joined The University of Texas at Arlington in summer 2011 for graduate studies. He had the opportunity to work as Graduate Research Assistant under Dr. Sahadat Hossain of Civil Engineering Department. The author's research interest includes soil-slope stability, geo-mechanics, earthquake engineering, geo-physical investigations and geotechnical aspects of landfills and soil liquefaction.