SUITABILITY OF CASUARINA EQUISETIFOLIA
AS UTILITY POLES IN SENEGAL

By
Babacar Salif Gueye

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE
in
Wood Science and Forest Products

APPROVED:

[Signatures]
Dr. John Muench, Chairman

Dr. John F. Siau
Dr. Robert Bush

Dr. Robert Youngs

November 1994
Blacksburg Virginia
SUITABILITY OF CASUARINA EQUISETIFOLIA AS
UTILITY POLES IN SENEGAL

By

Babacar Salif Gueye

Dr. John Muench, Chairman

Wood Science and Forest Products

(ABSTRACT)

The use of Casuarina equisetifolia trees grown in Senegal as utility poles was investigated as follows: (1) to determine the longitudinal air permeability of the species with regard to its treatability; (2) to determine the treatability of the wood using a full-cell process; (3) to determine the mechanical properties of the species relative to its use as utility poles in Senegal.

The mean superficial longitudinal air permeability of 60 specimens was 4990 cm³/(air)/cm s atm whereas the theoretical permeability was 4710 cm³/cm s atm. It was determined an average of 1830 vessels per cm² with a mean diameter of 117 microns and a volume fraction of 0.20. The presence of tyloses was not observed during the anatomical measurements.

As expected, the most important variables influencing the effectiveness of the preservative treatment were the impregnation pressure and the permeability of the specimens. Retention increased as the impregnation pressure was increased; and at a given pressure, retention was positively correlated to permeability. Since the wood seems to be fairly permeable, it can therefore be satisfactorily treated by controlling the impregnation pressure.
The results of static bending tests were compared to the theoretical maximum stress at ground line (R) of the different classes of utility poles used in Senegal. With an average modulus of rupture (MOR) of 108 megaPascals, the ratio of MOR to R varied between 2.12 to 2.34. This ratio provides evidence that *Casuarina*’s wood meets the mechanical requirements of the Standard NFC67-100, which sets the guidelines for utility poles in Senegal.
ACKNOWLEDGEMENTS

I would first like to thank my mother, Fatou Diop, without whom I wouldn't be where I am today. My sisters Laurence, Sira and Khoudia for their constant support. Also my wife, Lala for accepting to wait a so long time. My beloved son, Assane who was six months old when I left home. Thanks to Dr. John Muench for his constant support; Dr. John F. Siau who shaped the framework of this thesis, and guided with his abundance of ideas and willingness to discuss them; Dr. Robert Youngs, for his understanding, and constant support; Dr. Robert Bush, who is always available; and Dr. Charles Frazier, who made available to me his laboratory and instruments.

I would like to mention the help afforded to me by all the members of the Senegal Reforestation Project in Senegal; the invaluable support of Jim Fickes and Moctar Niang.

I'm also grateful to all the former and current staff members of the Office of International Development and Research, particularly Ruth Anne Niles, Denise Orden, and Karen Griggs.

Thanks to Tom Hergert, Eileen Moccia, and the Stith family for their friendship and always warm welcome into their home.

Appreciation is also given to all my friends at Virginia Tech.
TABLE OF CONTENTS

INTRODUCTION .......................................................... 1

PROBLEM STATEMENT AND JUSTIFICATION ............................. 3

STUDY OBJECTIVES ...................................................... 6

LITERATURE REVIEW ..................................................... 7

1.1 Utility Poles in Senegal ............................................. 8
  1.1.1 Characteristics of Utility Poles Used in Senegal ............. 8
  1.1.2 Importation of Utility Poles .................................. 11
  1.1.3 The Raw Material ............................................. 13

1.2 Permeability .......................................................... 17
  1.2.1 Darcy's Law .................................................... 17
  1.2.2 Specific Permeability ......................................... 18
  1.2.3 Poiseuille's Law .............................................. 21
  1.2.4 Kinds of Flow .................................................. 23
  1.2.5 Permeability and Anatomical Structure of Hardwoods ........ 25
  1.2.6 Sources of Variation of Permeability .......................... 30
  1.2.7 Methods of Measuring Permeability ........................... 32

1.3 Wood Preservation .................................................. 34
  1.3.1 Wood Preservatives ........................................... 35
  1.3.2 Effectiveness of Preserving Solutions ........................ 41
  1.3.3 Factors Affecting the Treatability of Wood .................. 43
  1.3.4 Methods of Improving the Treatment of Wood ............... 45
  1.3.5 Treating Processes ............................................ 47
1.3.6 Preservative Treatment of *Casuarina equisetifolia* ........ 53
1.3.7 Effects of Preservatives on Wood Properties .............. 55
1.3.8 Safety and Environmental Aspects of Wood

P..r..e..s..e..r..v..a..t..i..v..e

P..r..e..s..e..r..v..a..t..i..v..e

P..r..e..s..e..r..v..a..t..i..v..e

MATERIAL AND PROCEDURES ........................................ 59
2.1 Permeability and Pressure Impregnation .................... 60
2.1.1 Species and Sampling Procedure ........................ 60
2.1.2 Parameters and Experimental Design .................... 64

RESULTS AND DISCUSSION ........................................ 72
3.1 Permeability ................................................... 73
3.2 Vessel size and Number ...................................... 75
3.2 Pressure Impregnation ......................................... 80
3.2.1 End-Coated Specimens .................................... 80
3.2.2 Side-Coated Specimens ................................... 98
3.3 Mechanical Characteristics of *Casuarina* .................. 119
3.4 Economic Aspects of a Local Production of Utility Poles in

S..e..n..e..g..a

S..e..n..e..g..a

S..e..n..e..g..a

SUMMARY ............................................................ 130
CONCLUSION .......................................................... 132
APPENDIX A1: Pressure Impregnation Results for End-Coated Specimens .... 134
APPENDIX A2: Pressure Impregnation Results for Side-Coated Specimens ..... 135
APPENDIX B: Static Bending Results ............................. 136
REFERENCES ......................................................... 137
LIST OF TABLES

Table 1.1.1: Minimum Dimensions for SENELEC Poles .................................. 9
Table 1.1.2: Characteristics of SONATEL Poles ............................................. 10
Table 1.1.3: Imports of Utility Poles in millions of CFA Franc ......................... 12
Table 1.1.4: Unit cost after tax in CFA of electric poles ................................. 12
Table 1.2.1: Conversion Factors for Permeability Units ................................ 20
Table 1.3.1: AWPA recommendation for Chromated ZnCl ............................... 38
Table 1.3.2: CCA preservative formulations .................................................. 40
Table 2.1.1: Sampling Method for Impregnation ............................................. 69
Table 3.1.1: Permeability Results ................................................................. 74
Table 3.1.2: Vessel Number and Size ........................................................... 77
Table 3.2.1: Comparison of Mean Preservative Penetrations ............................ 82
Table 3.2.2: Effects of Impregnation Pressure on Preservative Penetration ....... 84
Table 3.2.3: Comparison of Mean Retentions for End-Coated Specimens .......... 91
Table 3.2.4: Effects of Pressure on Retention ............................................... 93
Table 3.2.5: Comparison Solution Retention for Side-Coated Specimens .......... 99
Table 3.2.6: Effects of Impregnation Pressure on Solution Retention for Side-
Coated Specimens ..................................................................................... 102
Table 3.2.7: Comparison of Mean Retention per Impregnation Pressure for
Side-Coated Specimens ........................................................................... 111
Table 3.2.8: Retention and Longitudinal Air Permeability ............................... 114
Table 3.3.1: Results of Static Bending Test with Load Applied at Mid-Span ..... 121
Table 3.3.2: Maximum Stress at Ground line for the Different Classes of Electric Poles Used in Senegal ................................. 123

Table 3.4.1: Estimation of supply of *Casuarina* electric poles .......................... 125

Table 3.4.2: Estimated Cost after Devaluation of Imported Poles and Average Cost of Locally Produced Poles ............................... 128
INTRODUCTION

Since its independence in 1960, Senegal’s rural development strategy has included two major components: (1) heavy state involvement in reforestation activities; (2) a strong coercive forest policy executed by the Forest Service.

The economic crisis of the late 1970s led the government of Senegal to formulate the New Agricultural Policy (NAP) in 1984. The NAP is part of the country’s structural readjustment plans which are focused on reducing state expenditure. The major objective of the NAP is the transfer of certain economic activities (notably production and marketing) from the state to the private sector (Delgado and Jammeh 1991). Among all the different rural development departments, the Forest Service was the least prepared to undergo the new policy for two reasons: (1) lack of marketing expertise in the Forest Service, and (2) growing trees as an economically viable activity has never been considered by the population who regard the natural forest as a free source of supply for their basic needs (Livingston and Gueye 1990).

The devaluation of the local currency in January 1993 played an important role in bringing the utility companies to express their need of using local species. In 1992, the electric company in association with the Forest Service conducted an inventory of Casuarina equisetifolia plantations for the supply of electric poles. Figure 1.1.1 shows the location of Senegal in Africa.
PROBLEM STATEMENT AND JUSTIFICATION

In 1986, the Senegal Reforestation Project (SRP) was initiated by the Government of Senegal in cooperation with the United States Agency for International Development (USAID). The major goal of the SRP is to promote private sector involvement in the forest sector. The Private Sector (PS) Office is one of the five components created within the SRP to carry out the new strategy. The Private Sector component of the SRP has as its main goals: (1) to conduct basic and feasibility studies for market opportunities of forest products and to implement the results, and (2) to provide support to woodlot owners or other entrepreneurs in the forest sector in marketing their products (USAID 1986). For the Forest Service, this new policy means not only more popular involvement in reforestation activities, but also development of a spirit of entrepreneurship in the forest sector and marketing support for forest products entrepreneurs.

In September 1988, the SRP contracted a marketing consultant to work in conjunction with the Private Sector component to identify existing opportunities concerning the exploitation of forest products for profit (Bender 1988). The consultant identified marketing possibilities in five main sectors: roundwood, sawnwood and veneer, combustibles, cashews, and gathered forest products. He also recommended that studies be conducted to determine the economic and technical feasibility of private sector investment in several areas, including wood preservation. Figure 1.1.2 gives the basic facts of the Republic of Senegal.
Size: 196,722 square kilometers (76,000 square miles)

Location: Between 12 and 17 degree north

Population: 8,000,000 (1990)
Growth Rate: 2.7% (3.83% urban; 2.07% rural)
Persons per square kilometers: 12 (1976); 35 (1988)
Ethnic groups: 12 (major five: Wolof, Serer, Poular, Mandingo, Diola)

Gross Domestic Product: 2.2 billion US dollars
Primary sector - 22% (Agriculture, Livestock, Fishing, Forest)
Secondary Sector - 28% (Mining, Manufacturing)
Tertiary Sector - 38% (Banking, Tourism)
Salaries - 14%

Agriculture
Employs 70% of labor force
Rainfed cultivation
Cash crops: peanuts, cotton, corn
Subsistence crops: millet, sorghum

Per Capita income: US $ 650
Literacy Rate: 37% for males; 19% for females
Life expectancy: 53 years for males; 56 years for females

Figure 1.1.2: Senegal: Basic Facts
The potential uses for locally produced wood are often limited due to the absence of wood treatment facilities in the country. The marketing opportunities for local roundwood would be greatly increased if there were a treatment facility in Senegal.

In 1990, The SRP contracted a local consultant to investigate the local demand for treated poles in Senegal. The consultant (Moreno 1990) interviewed the electric, telephone and railroad companies which are the main users of treated wood. The demand for treated poles was estimated at 5,000 units per year for wood power line supports, and 5,000 to 25,000 units per year for telephone poles, depending on new extensions (Moreno 1990).

The use of artificial plantations as a supply source is an important element of the new forest policy, which is intended to generate economic benefits for rural farmers by motivating them to plant and grow trees that produce commercially viable products. The more they can become involved in obtaining either useful products for themselves, or for barter, and/or cash sales, the more they are likely to develop enthusiasm for reforestation activities (Bender 1988). One of the recommendations of Bender (1988) was the use of Casuarina equisetifolia plantations as a supply source for a local pole treatment facility.
STUDY OBJECTIVES

The primary objective of this study is to determine the suitability of *Casuarina equisetifolia* as utility poles in Senegal. Specific objectives within this overall objective include:

1. To investigate the longitudinal air permeability of *Casuarina equisetifolia*.

2. To determine the treatability of *Casuarina* with a waterborne preservative.

3. To assess the mechanical properties of *Casuarina* with respect to its use as utility poles.

4. To discuss the aptitude of *Casuarina* plantations to meet the current demand of utility poles.
LITERATURE REVIEW
1.1 Utility Poles in Senegal

In Senegal, the National Electric Company (SENELEC) and the National Telecommunication Company (SONATEL) are the sole users of utility poles. There is no local production of utility poles. Europe is the major supplier with Finland, France, Spain and Germany being the principal sources. Since 1988, SENELEC has been importing *Eucalyptus* poles from Congo. In the early 1980s, SENELEC experimented with the local production of untreated teak poles. Most of those poles are still in service (Moreno 1990).

1.1.1 Characteristics of Utility Poles Used in Senegal

Wood electric and telephone poles used in Senegal must meet the requirements set by the NF C67-100\(^1\) and NF C11-201 Standards. Wood from which poles are processed must have the following characteristics: the treated wood must be free of any sign of biodegradation (fungi or insects) or physical defects that can affect its mechanical properties. The minimum dimensions required for the different categories of electric poles are presented in Table 1.1.1. Table 1.1.2 gives the requirements of telephone poles.

---

\(^1\) The standards NF C67-100 set the requirements for electric poles. The requirements for telephone poles are set by the Standards NF C11-201. Both are registered French Standards.
Table 1.1.1: Minimum Dimensions for SENELEC Poles

<table>
<thead>
<tr>
<th>Type of poles</th>
<th>Characteristics</th>
<th>length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>S 140</td>
<td>Top diameter (cm)</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Butt diameter (cm)</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Carrying load (N*)</td>
<td>4,250</td>
</tr>
<tr>
<td>S 255</td>
<td>Top diameter (cm)</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Butt diameter (cm)</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Carrying load (N)</td>
<td>7,500</td>
</tr>
<tr>
<td>S 325</td>
<td>Top diameter (cm)</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Butt diameter (cm)</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Carrying load (N)</td>
<td>9,600</td>
</tr>
<tr>
<td>S 430</td>
<td>Top diameter (cm)</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Butt diameter (cm)</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Carrying load (N)</td>
<td>12,500</td>
</tr>
</tbody>
</table>

Source: Moreno 1990

* The carrying load is expressed in newtons. It is determined based on a pressure of 480 bars applied at 25 cm from the top end.
Table 1.1.2: Characteristics of SONATEL Poles

<table>
<thead>
<tr>
<th>Length (m)</th>
<th>Min Top Diam (cm)</th>
<th>Min Butt Diam (cm)</th>
<th>Weight (Kg)</th>
<th>Ground Line Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>11</td>
<td>17</td>
<td>85</td>
<td>0.85</td>
</tr>
<tr>
<td>8</td>
<td>11</td>
<td>18</td>
<td>100</td>
<td>1.00</td>
</tr>
<tr>
<td>9</td>
<td>11</td>
<td>20</td>
<td>130</td>
<td>1.25</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>22</td>
<td>155</td>
<td>1.55</td>
</tr>
</tbody>
</table>

Source: Moreno 1990
Preservative Treatment

The Boucherie method\(^2\) is used to treat unseasoned poles, while dry poles are treated by the Bethel method\(^3\). The chemicals used are mostly: copper- sulfate, copper-chrome-arsenate salts and copper-chrome-borate salts. The choice of the chemical and its concentration depends on the species used. In addition, the butt of the pole must be treated a second time with a high concentration of creosote.

1.1.2 Importation of Utility Poles

SENELEC imports directly from the suppliers in Europe. The company is diversifying its supply sources by increasing its imports from Congo. SONATEL imports mainly through intermediary companies which gain the market through national or international bidding. Table 1.1.3 gives the importation of electric and telephone poles from 1982 to 1988. Table 1.1.4 gives the after tax prices for the two categories of poles.

\(^2\) In the Boucherie method, hydrostatic pressure forces the preserving solution from one end of the pole. The solution takes the place of the sap, which is pushed toward the other end (see section 1.3.5).

\(^3\) In the Bethel method or full-cell process, a preliminary vacuum is applied to remove the air from the wood cells. While still under vacuum, the preserving cylinder is filled with the preservative solution and the pressure is applied (see also section 1.3.5).
Table 1.1.3: Imports of Utility Poles in millions of CFA Franc

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CFA*</td>
<td>127</td>
<td>44</td>
<td>119</td>
<td>248</td>
<td>77</td>
<td>853</td>
<td>364</td>
</tr>
<tr>
<td>1,000 US $ **</td>
<td>211.6</td>
<td>73.3</td>
<td>198.3</td>
<td>413.3</td>
<td>128.3</td>
<td>142.2</td>
<td>606.6</td>
</tr>
</tbody>
</table>

Source: Moreno 1990

* These prices are 1990 prices. In November 1994 the CFA franc was devaluated and 1 French franc is now equal to 100 instead of 50 CFA franc which was the value of the currency before devaluation.

** 1 US $ = 6 French Francs = 600 CFA

Table 1.1.4: Unit cost after tax in CFA of electric poles

<table>
<thead>
<tr>
<th>Type</th>
<th>S 140</th>
<th>S 255</th>
<th>S 325</th>
<th>S 430</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>CFA franc</td>
<td>Type</td>
<td>CFA franc</td>
<td>US $ **</td>
</tr>
<tr>
<td>------</td>
<td>------------</td>
<td>------</td>
<td>------------</td>
<td>--------</td>
</tr>
<tr>
<td>S 140</td>
<td>47,746</td>
<td>7 m</td>
<td>28,000</td>
<td>46.7 *</td>
</tr>
<tr>
<td>S 255</td>
<td>50,486</td>
<td>8 m</td>
<td>35,000</td>
<td>58.3 *</td>
</tr>
<tr>
<td>S 325</td>
<td>63,916</td>
<td>9 m</td>
<td>45,000</td>
<td>75 *</td>
</tr>
<tr>
<td>S 430</td>
<td>85,464</td>
<td>10 m</td>
<td>57,000</td>
<td>95 *</td>
</tr>
</tbody>
</table>

Source: Moreno 1990
1.1.3 The Raw Material

The Natural Forest

This source of supply is mentioned, though it is not expected to produce sufficient poles on a regular basis for the following reasons: (1) the slow growth rate of the native species compared to the fast growing species introduced for reforestation purposes; (2) the difficulty in finding native trees that meet the physical requirements for utility poles such as the straightness of the stem, the presence of knots, the slope of the grain, and the width and number of the growth rings; (3) insufficient knowledge of their mechanical and physical properties; and (4) the high harvesting and processing costs involved because of the geographical dispersion of the trees.

Man-made Plantations

This type of forest is the most apt to supply utility poles. They are confined in well-defined zones with trees of even age. A financially sound harvesting and marketing program can bear replanting costs and allow new reforestation programs to be undertaken. The most promising species for local production of utility poles are: *Tectonia grandis* (Teak), *Casuarina equisetifolia* (Filao), and *Eucalyptus* spp.. Existing Casuarina plantations are located along the seashore and very close to the main urban areas; Teak plantations are located in the southern part of the country; and Eucalyptus plantations are composed of small wood lots spread all over the country (Figure 1.1.3).
Figure 1.1.3: Location of Teak and Casuarina Plantations
a) Teak Plantations

The first teak plantation was established in 1933 in the Kalounayes Forest (southern Senegal), and now covers 2,081 hectares (Ha). The close spacing adopted during the planting operations (2 x 2 m to 2 x 2.5 m) was not followed by a steady thinning program. Hence, the trees are very concentrated. Even though teak plantations are a potential supply source for utility poles, the inventory data available are quite old. The last inventory was done in the mid-1980’s.

b) Casuarina Plantations

Casuarina plantations are located in the traditional region called “the Niayes” along the northern fringe coast of the country. The area was heavily threatened by the advance of sand dunes inland. In 1948, a reforestation program consisting of monospecific plantations of Casuarina was initiated by the former French colonial authorities in order to protect the lands around Dakar, the capital city. Since independence the Senegal Forest Service has developed a massive reforestation program extending the land protection program to all the northern fringe coast. At the time of this study, there is a continuous band of Casuarina 150 Km in length and 400 m wide (6,000 Ha).

Although the primary objective of protection has been met, there is currently an urgent management problem facing the authorities: (1) there is no natural regeneration under the trees, (2) the plantations are getting old, and (3) the utility companies have expressed the need for using local trees to phase out their importation of poles. In 1990, in cooperation with the Canadian government, an inventory of the plantations was done and a management plan developed. This plan
would allow the trees to play their role of protection as well as of timber production, with the participation of the local population (Ndaiye 1992a).

c) *Eucalyptus* Plantations

*Eucalyptus* plays a major role in the reforestation programs in Senegal. Due to its fast growth and the straightness of the bole, it has been massively promoted by the Forest Service. Unlike teak and *Casuarina* plantations, which are concentrated in a specific areas, *Eucalyptus* plantations exist as small woodlots country-wide. In 1990, a survey was done by the SRP in order to assess the species’s standing timber. The results showed that there are 979 *Eucalyptus* woodlot in 694 villages. The surface area planted was estimated at about 1,373 Ha, with a total of 1,051,570 trees (Livingston and Gueye 1990). There are no data however, on the distribution of size of the trees. The economic and financial feasibility of local production of *Eucalyptus* utility poles is questionable due to the small size of the woodlot (0.2 to 1 Ha), and the difficulty of finding poles of good size in some areas.
1.2 Permeability

Permeability is important because it is used to predict the behavior of wood when subjected to various industrial processes such as preservative treatment, pulping, and drying. Many investigations have been undertaken in the last 35 years to increase the understanding of this subject: (e.g., Côté 1958; Wardrop and Davies 1961; Comstock 1967; Siau 1984; Choong et al. 1974; Tesoro et al. 1974; Wengert and Skaar 1975; Hofmann 1986). The following review of permeability related matters is mainly drawn from Siau (1984).

1.2.1 Darcy’s Law

The steady-state flow of fluids through wood and other porous solids is described by Darcy’s Law, which may be stated generally as:

Conductivity = Flux ÷ Gradient (Equation 1.2.1).

\[ k = \frac{QL}{A \Delta P} = \frac{[cm^3/cm\cdot s]}{cm^2/\text{atm}} \] (Darcy’s law for liquids) \[1.2.1\]

where \( k \) = the permeability [Darcy]; \( Q \) = the flow rate in [cm\(^3\)/s]; \( L \) = the length of the specimen in [cm]; \( A \) = the area of the specimen perpendicular to flow in [cm\(^2\)]; \( \Delta P \) = the pressure differential in atmosphere [atm]; and \( s \) = the time during which the flow occurred in second.
When Darcy’s Law is applied to gases, it takes into account the compressibility factor (Equation 1.2.2).

\[
K = \frac{QLP}{A \Delta P P} = \left[ \frac{cm^3}{cm^2 atm s} \right] \quad \text{(Darcy’s law for gases)} \quad [1.2.2]
\]

Where \( P \) = the pressure at which \( Q \) is taken; and \( \bar{P} \) = the average pressure of the fluid in the specimen.

In order to apply Darcy’s Law to a porous body such as wood, several requirements must be met: (1) the flow must be viscous and linear, with the flow rate proportional to the pressure differential and no energy loss because of turbulence or non-linearity; (2) the fluid must be homogeneous and incompressible; (3) the porous body must be homogeneous; and (4) there must be no interaction between fluid and substrate (Siau 1984).

1.2.2 Specific Permeability

Permeability as calculated with Equation (1.2.1) or (1.2.2) depends not only on the properties of the specimen and on the pressure differential, but also on the viscosity of the fluid. Comstock (1967) determined that permeability is a characteristic of the porous structure of the wood and is independent of the fluid used to measure it as long as the fluid does not swell the wood.
Therefore, specific permeability can be obtained from the product of permeability and viscosity as given in Equation [1.2.3] Siau (1984).

\[ K = k\eta \]  \hspace{2cm} [1.2.3]

Where \( K \) = specific permeability [darcy, \( \text{cm}^3/\text{cm} \), or \( \text{m}^3/\text{m} \)]; \( \eta \) = viscosity of fluid [centipoise, dyne \( \text{s}/\text{cm}^2 \), or \( \text{N} \text{s}/\text{m}^2 \)]; \( k \) = superficial fluid permeability in [\( \text{cm}^3/\text{cm} \text{ s atm} \)]. Table 1.2.1 gives conversion factors for permeability units.
Table 1.2.1: Conversion Factors for Permeability Units

<table>
<thead>
<tr>
<th>Conversion Factor</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>η of water at 20°C = 1 cp = 0.01 poise = 0.01 dyne s/cm²</td>
<td></td>
</tr>
<tr>
<td>η of air at 20°C = 0.0181 cp = 1.81 x 10⁴ dyne s/cm²</td>
<td></td>
</tr>
<tr>
<td>1 darcy = 9.87 x 10⁹ cm³/cm = 9.87 x 10⁻¹² m³/m</td>
<td></td>
</tr>
<tr>
<td>1 cm³/cm = 1.013 x 10⁶ darcy</td>
<td></td>
</tr>
<tr>
<td>1 darcy = 55.3 cm³ (air)/(cm atm s) at 20°C</td>
<td></td>
</tr>
<tr>
<td>1 cm³ (air)/(cm atm s) = 0.0181 darcy at 20°C</td>
<td></td>
</tr>
<tr>
<td>1 cm³ (fluid) cm/dyne s = 1.013 x 10⁶ cm³ (fluid)/(cm atm s)</td>
<td></td>
</tr>
</tbody>
</table>

Source: Siau 1984
1.2.3 Poiseuille's Law

Poiseuille's law describes viscous flow through a body comprised of parallel uniform circular capillaries. It relates the flow rate not only to the pressure differential but also to the size and number of tubes (Equation 1.2.4).

\[ Q = \frac{N\pi r^4 \Delta P}{8\eta L} \quad (\text{Poiseuille's law for liquids}) \quad [1.2.4] \]

where \( N \) = the number of uniform circular capillaries in parallel; \( r \) = the radius of the capillary in [cm]; \( L \) = the length of the capillary in [cm]; the other terms are the same than for the previous equations.

When Poiseuille's law is applied to gases, the gas expansion must be accounted for as it was in Darcy's Law for gases (Equation 1.2.5).

\[ Q = \frac{N\pi r^4 \Delta P \bar{P}}{8\eta L\bar{P}} \quad (\text{Poiseuille's law for gases}) \quad [1.2.5] \]
When Equations [1.2.2] and [1.2.5] are combined by the elimination of $Q$, the result shows that permeability is directly proportional to the number and size of the openings (Equation 1.2.6).

$$k = \frac{nmr^4}{8\eta} \cdot 1.013 \times 10^8 \frac{dyne}{cm^2\ atm} \tag{1.2.6}$$

where $k =$ permeability in cm$^3$ (air)/cm s atm; $n =$ the number of openings per unit area in cm$^{-2}$; $r =$ the mean radius of vessels in cm; and $\eta =$ the viscosity of the fluid.

Equation [1.2.6] may be used to calculate the permeability of a diffuse porous hardwood with open vessels, which structure approximates the parallel-uniform-circular-capillary model described by Siau (1984). Equation [1.2.6] can be used as a check for agreement between the measured permeability and that calculated. In hardwoods, where the open vessels are the primary flow path along the fiber axis, the term $n\eta r^2$ becomes the fractional cross-sectional area occupied by vessels, or the volume fraction of vessels. Then Equation [1.2.6] may be rewritten (Equation 1.2.7).

$$k = \frac{q_v r^2}{8\eta} \tag{1.2.7}$$

Where $q_v =$ area fraction of vessels.
1.2.4 Kinds of Flow

Siau (1984) describes the various kinds of flow which can occur in wood:

1. viscous or laminar flow
2. turbulent flow
3. nonlinear flow
4. molecular slip flow or Knudsen diffusion.

**Viscous Flow**

Viscous flow is directly proportional to the pressure differential supplied to overcome internal fluid friction forces in capillaries. When the Reynolds' number\(^1\) is equal to 2000, it is said to attain its critical value, and below this number, flow is completely viscous in a long straight capillary (Siau 1984).

**Nonlinear Flow**

Nonlinear flow which can be expected in an heterogenous substance like wood, is described by Siau and Petty (1979) as the result of kinetic energy losses in the entrance of straight round capillaries. In nonlinear flow, the pressure differential (ΔP) is proportional to \(Q^2\), and in turbulent flow, the pressure differential is proportional to \(Q^{1.75}\); therefore the two effects can be difficult to distinguish in many flow measurements (Siau 1984).

---

\(^1\) Reynolds' number (Re) is defined as a dimensionless term used to express the relative flow velocity for any capillary diameter.

\[
Re = \frac{2\bar{v}\rho}{\eta}
\]

Where \(Re =\) Reynolds' number, \(\rho =\) fluid density (g/cm\(^3\)), \(r =\) radius of capillary (cm), \(\eta =\) viscosity (s/cm\(^2\)), \(\bar{v} =\) average linear fluid velocity (cm/s).
Knudsen Diffusion or Slip Flow

Slip flow contributes to the magnitude of the measured permeability. It occurs when the mean free path of fluid molecules is in the same order of magnitude as the diameter of pit pores. As a result of slip flow, the specific permeability of wood is higher when measured with a gas than with a liquid. The mean free path of gas molecules can be obtained from Equation [1.2.8].

\[
\lambda = \frac{2\pi}{\bar{P}} \sqrt{\frac{RT}{M_w}}
\]  \[1.2.8\]

where \(\lambda\) = mean free path [cm]; \(\bar{P}\) = average pressure [dyne/cm\(^2\)]; \(R\) = universal gas constant \([8.31 \times 10^7\text{erg/mol K}\]); \(M_w\) = molecular weight [29 g/mol for air]; \(RT/M_w = 2.90 \times 10^4\) cm/s for air at 20°C and 1 atm. The slip flow may be obtained from Equation [1.2.9].

\[
Q = 3N \sqrt{\frac{RT}{M_w}} \cdot \frac{r^3\Delta P}{LP} \quad (Knudsen\ \text{equation\ of\ slip\ flow})
\]  \[1.2.9\]

Thus, the total flow is the sum of the Poiseuille flow, given by Equation [1.2.5] and the Knudsen flow given by Equation [1.2.9].
1.2.5 Permeability and Anatomical Structure of Hardwoods

In hardwoods, the vessel segments behave as open capillaries along the entire length of a wood specimen, when they are not occluded by tyloses. Their large diameter (compared with that of pit openings) makes the flow through fibers and longitudinal parenchymatous tissues insignificant by comparison. Thus, these paths are neglected in the simplified capillary model (Siau 1971, 1981). However, since lateral movement from the vessels to the other cells is limited to diffusion through the pit membrane, much of the wood may not be directly penetrated (Côté 1958). Figure 1.2.1 shows a generalized flow model for hardwoods.
Generalized Flow Model for Hardwoods (Siau 1971)

Figure 1.2.1: Flow in Hardwoods
Klinkenberg Equation

When Equations [1.2.5] and [1.2.9] are combined into one equation to determine the total flow, the resulting equation is called the Adzumi equation.

Adzumi's equation is based on the assumption that end effects can be ignored in the parallel capillary model (Equation 1.2.10).

\[
Q = \frac{N m r^4 \Delta P \bar{P}}{8 \eta L P} + 3.0 N \sqrt{\frac{R T}{M_w}} \cdot \frac{r^3 \Delta P}{LP} \tag{1.2.10}
\]

(Adzumi equation, viscous flow and Knudsen diffusion of gases)

Adzumi's equation can be rearranged by expressing the reciprocal average pressure (1/\(\bar{P}\)) as a function of permeability (k) (Siau et al. 1981). The resulting equation is called Klinkenberg equation (Equation 1.2.11).

\[
k_g = \frac{n \pi r^4}{8 \eta} + \frac{3.0 \ r^3 \ n \ \sqrt{\frac{R T}{M_w}}}{P} \quad \text{(Klinkenberg equation)} \tag{1.2.11}
\]

where \(k_g\) = the superficial gas permeability, intercept superficial gas permeability at infinite pressure; \(\bar{P}\) = average pressure (atm); \(r\) = the radius of the openings (cm); \(M_w\) = the molecular weight (29 g/mol for air, 28 g/mol for N\(_2\)); \(R\) = the universal gas constant (8.31 \times 10^7 \text{erg/mol}) and square root of \(RT/M_w\) equal 2.90 \times 10^4 \text{cm/s for air at 20 C and 1 atm. The specific permeability \(k\) may be obtained by extrapolation of \(k_g\) to zero reciprocal average pressure. The constant,
$0.4 \times 10^{-4}$ atm cm is based upon air flow under standard conditions.

The Klinkenberg equation (Equation 1.2.11) can be simplified further by the substitution of mean free path in Equation [1.2.8] and by the substitution of k for the viscous term in Equation [1.2.6]. The resulting terms yield Equation [1.2.12].

\[ k_s = k \left(1 + \frac{3.8\lambda}{r}\right) = k_s \]  

[1.2.12]

where \( s = \) the slip-flow factor

The slip flow factor represents the factor by which the viscous flow term is increased at a given average pressure due to the slip flow component. Rewritten, Equation [1.2.11] becomes (Equation 1.2.13), assuming air at 20 °C,

\[ r = 0.40 \times 10^{-4} \text{ atm cm}^2\text{dyne} \times \frac{\text{intercept}}{\text{slope}} \]  

[1.2.13]

The Klinkenberg plot provides a linear relationship between permeability and reciprocal average pressure, assuming that there is no nonlinear flow from turbulent flow or kinetic energy losses. (Siau et al.1981).

**Pit Pore Radius**

The expression, pit pore, pit pore size, or pit pore radius, refers to the opening of the pit membrane of interconnecting pits. Using Klinkenberg plot, it is possible to calculate the mean radius \( r \) of the pit openings using Equations [1.2.12] or [1.2.13].
However, it has been shown that hardwoods with high axial permeability do not always obey the linearity of the Adzumi or Klinkenberg equations, but sometimes follow a curvilinear line (Siau et al. 1981; Comstock 1967).

Therefore, the effect of non-linear flow in short capillaries must be considered when they are used for flow measurement or viscosity determination (Siau and Petty 1979). Two correction factors may be applied for short capillaries like pit pores (Siau 1984): the Couette correction factor and the Clausing factor. These two factors must be applied to the Adzumi and Klinkenberg equations for the determination of the radius (r).

The Couette correction factor is applied to the Poiseuille equation (Equation 1.2.5) to account for end resistance. This is done by multiplying the radius obtained from Equation [1.2.5] by the factor \((1 + 1.2 \frac{r}{L})\).

The Clausing factor \(K_c\) is applied to the slip flow term in Equation [1.2.10]:

where:\n\[ K_c = \frac{1}{1 + 0.5 \frac{L}{r}} \text{ for } \frac{L}{r} \leq 1.5 \text{ or } \]
\[ K_c = \frac{1}{1 + 0.375 \frac{L}{r}} \text{ for } \frac{L}{r} > 1.5 \]

When combined, these two correction factors are then to give an overall correction factor (cc), as given in Equations [1.2.14a] and [1.2.14b].
\[ cc = \frac{L/lr + 1.2}{1.33Llr + 2.67} \quad \text{for } L/lr \leq 1.5 \]  

\[ cc = \frac{Llr + 1.2}{Llr + 2.67} \quad \text{for } L/lr > 1.5 \]  

where \( L/lr \) = the ratio of length to radius of a capillary. The pit pore radius calculated from Equation [1.2.13] must be multiplied by the factor \( cc \).

1.2.6 Sources of Variation of Permeability

It has been shown that the longitudinal permeability of diffuse porous hardwoods mainly depends on the size and abundance of the vessels. Therefore, any circumstances or conditions which influence the structure of the vessels are also likely to affect permeability. The most important of these effects are the differences between sapwood and heartwood, the location within the tree, the specific gravity and moisture content, and the drying process.

Sapwood-Heartwood Differences

Great variations have been reported in longitudinal permeability between sapwood and heartwood, within species, and even within wood specimens taken from different locations in the same tree (Choong et al. 1974; Tesoro et al. 1974; Wardrop and Davies 1961; Siau 1971; Siau 1984).
In heartwood of angiosperms resistance to flow is increased by the formation of tyloses in vessels, thus reducing the initial penetration, and by the incrustation of the pit membranes (Côté 1958). It is therefore appropriate to separate the results of permeability measurements between sapwood and heartwood.

**Location within the Tree**

Choong et al. (1974) determined that a large difference in permeability occurs between the longitudinal and transverse directions. Their results showed a wide range of permeability ratios in a given structural direction as well as between structural directions. They reported that when the extreme range of values is taken, the ratio for longitudinal to tangential permeability varies from 12,000 to 1 for post oak (*Quercus stellata*) to as high as over 1,000,000 to 1 for other oaks. In the same study, even though the permeability difference between radial and tangential directions was not statistically significant in general, the mean values were higher for radial than for tangential permeability. However, Siau (1984) cited Comstock (1975 unpublished results) who found little difference between tangential and radial permeability.

**Treatments to Increase Permeability**

Pit aspiration is the greatest factor that influences permeability in softwoods of the *Pinaceae* family (Siau 1984). Most procedures used to enhance permeability are therefore aimed at avoiding pit aspiration. The hardwoods and other softwoods do not have pit tori and therefore are not affected by this phenomenon. The main factor affecting permeability for hardwoods is the presence of tyloses that could block the vessels.
In a study of the effect of surface preparation on gas permeability of wood, Choong et al. (1975) used purified nitrogen gas to measure the permeability of twenty-seven longitudinal and fifteen transverse samples, using four surface conditioning methods (band sawn, sanded, scalpel-cut, and laser-cut). The results showed no significant difference in longitudinal permeability between laser-cut and scalpel-cut surfaces, but the longitudinal permeability of sanded surfaces was significantly (1 percent level) lower than for sawn surfaces. Moreover, surfaces cut with the laser and the scalpel had significantly higher permeability values than did the sawn and sanded surfaces.

1.2.7 Methods of Measuring Permeability

Permeability measurements are mainly used to predict the treatability of wood with liquids. If gaseous permeability is corrected for slip flow, gas expansion, and viscosity, it is generally regarded as a reliable indicator of treatability (Comstock 1967; Choong et al. 1974).

Liquid Permeability

Comstock (1967) determined that permeability of wood is independent of the fluid used to measure it as long as the fluid does not swell the wood. Due to the interaction between the hydroxyl groups of polar liquids such as water and the wood cell wall, and the presence of particulate matter, ultrafiltration and degasification of the liquid may be necessary in order to obtain a constant flow rate.
Gas Permeability

For gas permeability measurements, three adjustments must be made in order to obtain the equivalent liquid permeability.

Gas expansion: the use of the modified Darcy's Law for gases (Equation 1.2.2) accounts for expansion of gases due to the drop in the pressure along the sample.

Viscosity: the specific permeability which is independent of the fluid employed is as calculated with Equation [1.2.3].

Slip flow: to determine the effect of slip flow, measurements must be made at different mean pressure levels. The intercept of the Klinkenberg plot may then be assumed equal to the liquid permeability.

From gas permeability measurements, the mean size and concentration of pit pores can be calculated (Siau 1971; Siau 1984; Comstock 1967; Siau et al. 1981).

According to the literature, the following methods are used to measure gas permeability:

1. the rising-water volume-displacement method;
2. the falling-water displacement method; and
3. the rotameter method.

These methods of permeability measurement are described in detail by Siau (1971). Methods 1 and 2 are unsteady-state methods. The first one is more suitable for woods of high and low permeability. The second method is mostly indicated for measuring very high permeabilities.
1.3 Wood Preservation

The foremost purpose of wood preservation is to protect the wood from the attack of decay fungi, insects, or marine borers. The effectiveness of a preservative is influenced not only by the protective value of the chemical itself, but also by the method of application and the extent of penetration and retention of the preservative in the treated wood (Findlay 1985).

The species of wood, proportions of heartwood and sapwood, heartwood penetrability, and moisture content are among important variables influencing the results of treatment. The amount of preservative required to protect a given volume of wood against any particular fungus can be determined, and is called "toxic limit" or "threshold value" (Findlay 1985). Neumark (1953) defines the toxicity limit as the lowest chemical retention at which larval activity is made impossible, the larvae dying either from lack of food or poisoning or from both of these factors jointly.

The requirements that a preservative must meet are: (1) be toxic to wood destroying organisms, its value as a preservative must be supported by field and/or service data; (2) to possess satisfactory physical and chemical properties which govern its permanence under the conditions for which it is recommended for use; (3) be relatively free from objectionable qualities in handling and use; (4) be satisfactory to laboratory and plant control; (5) be available under provision of current patent, and (6) be in actual commercial use (Findlay 1985).
1.3.1 Wood Preservatives

Wood preservatives are classified into two general categories: oil-borne preservatives and waterborne preservatives. Oil preservatives are creosote-based solutions, pentachlorophenol solutions, and water-repellent preservatives. Waterborne preservatives are used in water solution and include acid copper chromate (ACC), ammoniacal copper arsenite (ACA), chromated copper arsenate (CCA, type A, B, and C), chromated zinc chloride (CZC), and fluor chrome arsenate phenol (Findlay 1985).

Oil-borne Preservatives

When treated with an oil-based preservative, wood does not swell, but it may shrink if it loses moisture during the treating process. Creosote and petroleum solutions help protect the wood from weathering outdoors, but may adversely influence its cleanliness, odor, color, paintability, and fire resistance in use. Another disadvantage of oil preservatives is their bulky nature, making them difficult to transport. The American Wood Preservers’ Association (AWPA) Standard P8-77 determines the standards for oil-borne preservatives.

Coal-tar creosote is a residual product from the distillation and processing of coal tar. Its main advantages are: (1) high toxicity to wood destroying organisms; (2) relative insolubility in water and low volatility; (3) ease of application; (4) and ease with which its depth of penetration can be determined. Creosotes distilled from tars other than coal tar are used to some extent for wood preservation, although they are not included in current AWPA specifications. These creosotes are generally less effective than coal-tar creosote.
Pentachlorophenol preservatives are, in general, water repellent solutions containing generally 5% (by weight) of this chemical (there is also a water-borne pentachlorophenol). Depending on the end-use of the treated wood, a heavy (Type A) or light (Type C) hydrocarbon solvent may be used as specified by AWPA P9-77.

**Water-borne Preservatives**

Water-borne preservatives are used for a range of end-uses. The most important of this group are the copper/chromium mixtures of which copper/chromium/arsenic is the most common. They are introduced into the wood as a water-soluble mixture of salts which then react in such a way as to render them water-insoluble. This enables the treated timber to be used in damp or wet conditions without subsequent loss of protection by leaching. The other main water-borne preservatives, such as the boron compounds and the fluorides, remain water-soluble throughout their service lives and are therefore prone to leaching if placed in service environments where water can permeate the wood.

Standard wood preservatives used in water solution include acid copper chromate (ACC), ammoniacal copper arsenate (ACA), chromated copper arsenate (CCA types A, B, C), chromated zinc chloride (CZC), and fluor chrome arsenate phenol. The AWPA standards P5-83 describes and defines the use of waterborne preservatives.

In this study, zinc chloride will be used to determine the treatability of *Casuarina equisetifolia*, due to the fact that the chemicals are easy to obtain, and the depth of penetration can be visually determined.
Any future preservative treatment program in Senegal must take into consideration the advantages and inconveniences of water-borne preservatives versus oil-borne preservatives. CCA is another water-borne preservative widely used in the African continent and around the world. A review of CCA characteristics was also done due to its wide use in the African continent, mostly in sub-saharan Africa (Findlay 1985). Any preservative, however, recommended by the AWPA can be used.

a. Zinc Chloride

Chromated zinc chloride (CZC) was developed to reduce the leaching and corrosiveness of pure zinc chloride which was used in large quantities during the creosote shortage following World War II (Findlay 1985). The formulation of CZC is relatively simple, since there are only two ingredients. Table 1.3.1 gives the AWPA recommended composition by weight for zinc chloride.
Table 1.3.1: AWPA recommendation for Chromated ZnCl

<table>
<thead>
<tr>
<th>By Weight</th>
<th>Composition (%)</th>
<th>Minimum (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc as ZnO</td>
<td>80</td>
<td>76</td>
</tr>
<tr>
<td>CrO3</td>
<td>20</td>
<td>19</td>
</tr>
</tbody>
</table>

Source: AWPA P5-83
b. Chromated Copper Arsenate (CCA)

There is a growing use of chromated copper arsenate in West Africa because the product is cheaper than creosote, has world-wide recognition, and is considered by developing countries as a means to earn valuable foreign exchange by exporting their primary timber species, which are also naturally durable, and to utilize treated secondary species less durable for domestic use (Findlay 1985). In West Africa; Nigeria, Ghana, Gabon, Ivory Coast, and Liberia have CCA wood preservation facilities (Findlay 1985). Chromated copper arsenate preservative formulations are classified into three types known as Types A, B and C. Table 1.3.2 gives the relative amounts by weight of active oxides that are hexavalent chromium (CrO₃), copper oxide (CuO), arsenic (As₂O₅), and the minimum and maximum limits, according to the AWPA P5 1983. Type C is the formulation recommended for use by the Standard NF C11-201 (1980) and NF C67-100 (1982).
<table>
<thead>
<tr>
<th>By Weight</th>
<th>Type A (%)</th>
<th>Type B (%)</th>
<th>Type C (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium</td>
<td>65.5</td>
<td>59.4</td>
<td>69.3</td>
</tr>
<tr>
<td>Copper</td>
<td>18.1</td>
<td>16.0</td>
<td>20.9</td>
</tr>
<tr>
<td>Arsenic</td>
<td>18.4</td>
<td>14.0</td>
<td>19.7</td>
</tr>
</tbody>
</table>

Source: AWPA 1983
1.3.2 Effectiveness of Preserving Solutions

The most important factors affecting the effectiveness of preservative solution are penetration and retention. Almost all poles purchased are inspected for conformance with results-type specifications, because an accurate measure of penetration and retention will indicate whether the wood was properly treated (Nicholas 1973).

Nicholas (1973) described several factors that affect penetration other than treating techniques. These are: dryness, sap stain, pit aspiration, cleanliness of solution, sapwood depth, off-center pith, thickness of the growth rings, incising technique, species, density, splits, and checks. However, regardless of what causes lack of penetration, it affects service life. While it often happens that the depth of penetration is approximately uniform on all sides of poles, sometimes the penetration is much deeper at some points than others, leaving an untreated core of wood of irregular cross section. In general, the depth of sapwood controls the depth of penetration.

The retention of preservative is the most important factor influencing the effectiveness of preservative systems in extending the service life of treated wood. Retention of preservative at the wood-soil boundary must be continually high enough to discourage termite penetration and fungal growth. During the service life of wood there may be continuous depletion, such as with oil-borne preservatives. This means that the retention required immediately after treatment must be the amount needed to protect, plus an amount to be lost through migration and depletion from leaching or bleeding.
Bleeding of preservative oils refers to the exudation of oily materials, such as creosote, from the outer fibers of the treated wood. It is considered to be the result of the heating of the pole by solar radiation (Nicholas 1973). Bleeding may also be caused by internal air pressure created by aspirated pits during the drying process. This trapped air then pushes the oil out until the pressure is released (Nicholas 1973). Preservative salts or components of oils that are water soluble will leach from treated wood according to the gradient difference between the water and the preservative carrier (Nicholas 1973).

The AWPA 1983 describes the different methods of analysis for determining penetration of preservatives and fire retardants. This study will be limited to assessing the penetration of zinc. This method uses Potassium Ferricyanide at 1%, Potassium Iodide at 1%, and a Starch indicator. By spraying a mixture of the three components over a fairly dry piece of wood treated with zinc chloride, the presence of zinc is indicated by a blue color. This method, therefore, can indicate the depth of penetration of the preservation by simple measurement with a ruler.
1.3.3 Factors Affecting the Treatability of Wood

Effect of Liquid Properties

Certain properties of the preservative liquid are also of significant influence. These properties include the solution viscosity, the presence of dissolved gases which may escape and form bubbles during flow, and the presence of particulate matter resulting from reactions of the preservative chemicals or from wood extractives which have been removed by the solvent action of the preservative solution (Nicholas 1973).

Viscosity has been cited as one of the most obvious properties of a liquid affecting its flow in wood. If Poiseuille’s law for flow of liquids is obeyed (see section 1.2.3), the velocity of flow would be inversely proportional to viscosity. Nicholas (1973) has shown however, that at least for certain oils, the viscosity is less important than predicted by Poiseuille’s law, since the fractional void volume filled in a given period of time is inversely proportional to the logarithm of the reciprocal of the viscosity raised to the 0.42 power. In general, there is a significant effect of reduction of solution viscosity upon treatment. This is mostly accomplished by heating oil-borne preservatives. A similar effect results from the heating of wood in waterborne preservatives. The AWPA Standards C1-82 recommend maximum temperatures between 120°F and 140°F for waterborne preservatives, and up to 210°F for heated oil-borne preservatives for most species.
The presence of air-liquid interfaces in the intervesSEL pitting makes it difficult, if not impossible, to treat most wood at low pressures. These air-liquid interfaces can be generated by the existing moisture content of the wood prior to treatment; and also the entering preservative solution has sufficient vapor pressure so that condensation can occur in the pit pores prior to the penetration of the liquid. It is physically impossible to reduce the pressure below the vapor pressure of water and remove all the air, therefore, it is impossible to prevent the formation of air-liquid or vapor-liquid interfaces during the impregnation process (Nicholas 1973).

As treating solutions are continuously reused, they undergo an aging process which results in a build-up of particulate matter. This particulate matter can reduce the size of pore openings by accumulation, therefore influencing negatively the flow of the preservative solution into the wood. Thus, periodic removal of this particulate matter would result in better treatment.

**Effects of Physical Factors**

These factors deal with the use of pressure, vacuum, and/or time to treat the wood. Due to the variability of the structure of wood itself and the factors related to the characteristics of the preservative carrier, physical means such as pressure are often used to overcome capillarity and force air-liquid interfaces through small pit openings. In some cases, wood is treated by dipping at atmospheric pressure or by applying a preliminary vacuum.
1.3.4 Methods of Improving the Treatment of Wood

Nicholas (1973) discussed three basic methods of improving treatability: (1) altering the wood characteristics, (2) altering the treating process, (3) altering the treating solutions.

Altering the Wood Characteristics

The basic objective in altering the wood characteristics is to open up the structure or to increase the effective pore size of wood so that it can be adequately treated without using excessive pressure.

Incising is an effective and cheap method of improving the treatability of wood. It consists of increasing the permeability of the wood by alternating incisions along and across the piece. Compression is also a means of improving treatability. Its advantage over incising is that there is less disruption over the surface.

Steaming is another means of improving the permeability of wood, that is, its treatability. The wood is generally steamed while green, prior to treatment. Steaming is said to allow the wood to maintain its green permeability after drying by reducing the effectiveness of pit aspiration. Its negative action on the mechanical strength of the wood however also has to be taken into consideration (Nicholas 1973).

The removal of extractives from the pit membrane is another method to improve treatability by increasing the effective pit pore size. However, the commercial feasibility of this method has been questioned (Nicholas 1973).
Chemical modification can also be used to increase permeability. A chemical reagent such as sodium chlorite, pulping liquors, acids, and bases have been found to improve the permeability of wood (Nicholas 1973). Excessive strength loss may result however, from these treatments. Gas-phase treatment is another chemical method to improve treatability, by using a gas to alter the pit membrane. Its advantage is that the gas does not leave a residual liquid that must be removed prior to treatment. No matter what type of chemical treatment is used, it is always difficult to find a chemical selective enough to degrade the pit membrane without affecting the cell wall.

Microorganisms and enzymes can also be used to improve permeability. Ponding is a means employed to selectively degrade wood by immersion in water. It has been successfully used for *Casuarina* in India (Narayanappa 1988).

**Altering the Treating Process**

This is done by using different treating cycles. The variation of the impregnation pressure, the variation between vacuum and pressure throughout the cycle (oscillating pressure), the use of shock waves, and the hydro-jet technique are all different methods used to improve treatability. High pressures can significantly improve the treatment of refractory wood; and the oscillating pressure method has been found to have little effect on dry wood (Nicholas 1973). The pros and cons of these different methods have been thoroughly discussed by Nicholas (1973).
Altering the Treating Solution

The role of the viscosity of the liquid, dissolved gases, and particulate matter have been discussed in 1.3.3. The use of additives to alter treating solutions, a proper selection of chemicals and additives for formulations, can also yield improvement.

1.3.5 Treating Processes

It should be mentioned that the term "pressure treatment" is used here to describe processes where high hydrostatic pressure is applied to a liquid preservative that surrounds the wood in a closed vessel. All other methods are placed in a second category designated as "non-pressure", even though the movement of the preservative into wood is still caused by some form of pressure.

Pressure Processes

Pressure treatment is an effective method of protecting wood. Pressure processes are performed in steel cylinders ranging from 122 cm to 305 cm in diameter, and up to 53 m in length, and are capable of withstanding pressures up to 200 psi (1.34 MegaPascals). Cylinders are generally equipped with steam-heating coils to maintain temperatures of the preservative solution during the processing cycle. Vacuum pumps capable of applying a vacuum of 24 inches (610 mm) are part of the equipment. Air compressors and air-pressure receivers provide air pressure which is used in treating processes to apply pressure to the cylinder, operate instruments, and in some cases to manipulate large valves. A boiler plant is also necessary to provide steam for heating and processing. The material to be treated is loaded on metal buggies which are moved on steel tracks.
1. Full-Cell or Bethel Process

The object of the full-cell process is to fill the cells of wood to capacity to ensure a maximum amount of preservative retention. The full-cell processes are almost always employed with aqueous solutions. They are used with creosote or other oil-borne preservatives only in special applications, such as marine piles.

After the cylinder is charged, a preliminary vacuum is applied in order to remove the air from the wood cells. Most treatment specifications require that the vacuum be equivalent to not less than 22 or 24 inches of mercury (558.8 - 609.6 mmHg) and held for a period of 15 minutes to one hour (Nicholas 1973). While the vacuum is maintained, preservative solution is introduced into the cylinder, until the cylinder is completely filled with preservative solution and the wood is totally immersed in the solution. The vacuum must be maintained throughout the filling period to avoid compression of air or vapor above the preservative solution. Such compression would lead to differential retention between the material at the top of the cylinder and the bottom. When the cylinder is completely filled with solution, pressure is applied directly to the system until refusal. It is recommended that, when maximum retention is specified, the pressure and temperature should be kept constant or be increased within a range consistent with good practice until the quantity of preservative absorbed in each of any two consecutive half hours is not more than 2% of the amount already injected (Nicholas 1973).

When the impregnation period is terminated, pressure is released slowly to one atmosphere and the treating solution is returned to the storage tank. The full-cell treating cycle varies considerably from one product or species to another.
2. Empty-Cell Processes

There are two empty-cell processes; the Lowry and Rueping processes. In both, air is compressed in the wood. Following the process cycle, the air expands and forces excess preservative out of the wood.

*Lowry process.* In this process, wood is introduced into the cylinder and preservative solution is introduced at atmospheric pressure. When the cylinder is filled with preservative, pressure is applied to the system, forcing the preservative into the wood. A final vacuum is applied after the pressure is released, allowing the remaining air to expand and forcing the excess preservative from the wood. In this process, the preservative penetrates as deeply as with the full-cell process, but less preservative remains in the wood. One of the advantages of this process is that no more equipment is needed than is required for the full-cell process.

*Rueping process.* The principal difference between this process and the Lowry process is that in the Rueping process, air is forced into the cylinder prior to filling it with preservative. After the cylinder is charged, the system is made airtight and air pressure is applied, filling the wood with compressed air. The preservative is then forced into the cylinder while the preliminary air pressure is maintained constant. When the cylinder is filled with preservative, additional pressure is applied to the system, forcing preservative into the wood and further compressing the preliminary air. A final vacuum is applied after the pressure is released, allowing the compressed air remaining in the wood to expand, and pushing the excess preservative out of the wood.
3. Cellon® Process

The principle of the Cellon® process for impregnating wood is that the preservative carrier is essentially evaporated from the wood, leaving only the preservative in the wood. This takes place as part of the treating process while the wood is still in the cylinder. The Cellon® process is basically a three-part system - the treating solution, the treating cycle, and the equipment.

The treating solution is composed of a low-boiling point carrier in which the preservative is dissolved. If the preservative is not readily soluble in the carrier, an auxiliary solvent may be a part of the treating solution. One treating solution formulation which has been used commercially consists of liquefied petroleum gas (butane), isopropyl ether, and pentachlorophenol, which are the carrier, auxiliary solvent and preservative respectively (Nicholas 1973).

The Cellon® treating cycle may be either full-cell or empty-cell. After the cylinder is charged and made airtight, the unit is purged using inert gas. A vacuum is applied prior to filling the cylinder with preservative, and then pressure is applied to force the solution into the wood. When the desired amount of preservative solution is forced into the wood, the solution is returned to a storage tank, and a vacuum is then applied to the cylinder to reduce the boiling point of the carrier so that it will evaporate from the wood. The vapors are collected, cooled, and returned to the storage tank.
4. The Boucherie Method

In this method, a cap containing a preservative solution is fixed at the butt end of a freshly felled pole. The cap is connected by a rubber tube to a reservoir at a much higher level, so that a hydrostatic pressure is exerted, slowly forcing the liquid through the cell cavities of the wood, while at the same time the sap is driven out at the top end. Neumark (1953) used a similar process to treat *Eucalyptus* poles in Israel. He used different hydrostatic pressures in order to determine their influence upon the speed of the flow. The results showed an appreciable increase of flow, indicating a proportional relationship between the speed of the flow and the pressure applied. Therefore, the author set up a modified method using a small air compressor to build up pressure in a tank containing the preservative.

Non-Pressure Processes

Although most treated wood is processed by pressure methods, there are several non-pressure methods. The choice of a particular method depends on the end-use, the type of wood, and economical factors.

1. Diffusion Processes: Diffusion-treatment processes rely on movement of aqueous solutions of chemicals into unseasoned wood by diffusion. Nicholas (1973) distinguishes three different diffusion processes: (1) immersion in a single-preservative solution, (2) the application of preservative pastes on the surfaces of the wood, and (3) immersion of wood in two separate solutions which result in the formation of an insoluble compound within the wood (double-diffusion). Diffusion always occurs whether the green wood is only painted, sprayed or dipped in the solution.
Findlay (1975) indicated some modifications in the double-diffusion process that can improve preservative retention. These are: (1) allowing the material to partially dry (30-40% moisture content) before treatment; (2) incising the material before treatment; and (3) applying heat to the first treating solution. The factors that influence the final result are the length of the immersion period, the nature of the preservative and the degree to which it penetrates and distributes itself after treatment when the solvent has dried out (Findlay 1985).

The Cobra process is another ingenious way of introducing preservative salts into poles. In this method, a preservative paste composed of fluorides, dinitrophenates and arsenates, is injected into the wood through a hollow flat needle or tooth, which is forced in parallel to the grain to a depth of about 50 mm (2 ins) so that little damage is done to the wood with no appreciable weakening results (Findlay 1985). The injections are given to the zone just above the ground level where the risk of decay is greatest. This method is most commonly used for the treatment of standing poles that have begun to show signs of decay.

2. Thermal Process: In the thermal process, hot preservative is pumped into a tank containing the wood until the wood is completely immersed. The solution is maintained at the same temperature (200 - 235°F) for a period of several hours, after which it is pumped from the treating tank. Immediately the tank is flooded with cooler preservative solution (approximately 100°F) and allowed to remain there for a shorter period. This cooler preservative solution causes hot air in the wood cells to contract, creating a vacuum which draws the preservative into the wood (Nicholas 1973).
Findlay (1985) describes another version called the open tank and cold process. In this process, the wood is submerged in a bath of preservative which is heated for a few hours and then cooled while the wood is still immersed in the liquid. During the heating period, the air in the wood cells expands and much of it escapes as bubbles. When the wood cools again, the air remaining in the cells contracts, thus creating a partial vacuum, and the atmospheric pressure then tends to force the preservative into the pores of the wood. So it is during the cooling period that much of the absorption takes place. The greater the difference in temperature between the hot and the cold bath, the greater the absorption.

1.3.6 Preservative Treatment of *Casuarina equisetifolia*

*Casuarina*'s wood has been used in India for several decades as mining posts. The wood has also been investigated by the Australians, and the Germans. The first investigations about the species grown in Senegal was done in 1993.

Sharma et al. (1984) treated green fence posts of *Casuarina equisetifolia* with CCA concentration of 15% by sap-displacement method. In order to determine the distribution of chemicals, the posts were divided into five equal sections and a disc of 2.5 cm thickness was cut from the middle of each section. The discs were then analyzed for absorption of the various chemicals. The authors noticed a high retention of arsenic pentoxide compared to sodium dichromate and copper sulfate. This indicated that the specified proportion of these constituents in CCA was not maintained in different regions of the posts. An average chemical retention of 33.68 Kg/m³ was observed.
Narayanappa (1988) treated three sets of 5 samples of *Casuarina equisetifolia* for 4 weeks with 6% ACC solution (3% cooper sulphate, 2.7% sodium dichromate and 3% acetic acid added to adjust the pH). After air drying for 15 days, the depth of preservative was measured with the indicator S-Diphenyl carbazide 0.5 mg in 50 ml isopropyl alcohol and 50 ml distilled water. The penetration was then calculated as a percentage of the total cross sectional area. The results showed a significant increase in the absorption of chemicals in ponded samples. It was also noticed that the retention of preservative increases with the increase of the diffusion period, but decreases with the increase in size of the specimens. The effect of the ponding period became insignificant after one month. One month ponding period enabled retention to be achieved in only one week, while the retention for un-ponded specimens was achieved in four weeks. Sharma (1984) observed also the same irregular penetration of the chemicals. This indicated an inverse relationship between the ponding of *Casuarina* and the period of diffusion treatment required to achieve adequate retention of preservatives.

Sharma et al (1988) treated *Casuarina equisetifolia* poles with CCA, ACC and CCB preservative compositions at concentration of 4.27%, 5.9% and 4% respectively by the full-cell process under 70 psi pressure for 2 hours. Only sapwood was readily treated. A graveyard test of the treated poles showed that after 26 months service, the depth of decay was found to be 1-4 mm in untreated poles and almost nil in the treated poles.
OSMOSE (1993) evaluated CCA treatability of *Casuarina equisetifolia* samples from 10 year old trees growing in Senegal using a full-cell process. Several samples, approximately 5.7 x 5.7 x 30.4 cm, of rough cut, wet *Casuarina* were full-cell treated with CCA at 2% concentration according to the following schedule: 30 min., 25" Hg vacuum, followed by 4 hours at 140-155 psi pressure. After treatment, the samples were analyzed for copper penetration according to the AWPA Standard A3, Method 2, (Chrome Azurol S). Based on this treatability study, *Casuarina equisetifolia* appeared to be readily treated with CCA wood preservative, as almost complete cross sectional penetration was obtained on each sample. However, the samples were all sapwood. In addition, considerable splits and checks occurred during the drying process (air drying). Therefore, one of the recommendations was to find a way to dry the wood without excessive checking prior to preservative treatment if this wood species is to be used as a pole species.

Sosa and Hesse (1989) pressure treated *Casuarina* with creosote. At a final pressure of 10 bar, 100% penetration of sapwood was achieved, against only 66% for heartwood. This showed a satisfactory treatability of *Casuarina*'s sapwood, compared to the heartwood.

### 1.3.7 Effects of Preservatives on Wood Properties

Several researchers have investigated the physical and mechanical properties of treated wood (Kumar and Jain 1978; Ethington 1972; Gilfedder et al. 1968; Winandy and Boone 1988). The effects of the chemicals composing the treating solutions and their nature determine most of the time the end-use of the treated wood.
Winandy and Boone (1988) studied the effects of CCA preservative treatment and redrying on the bending properties of southern pine lumber. Specimens of 2 x 6 inches were treated using CCA type C and a modified full-cell process, with target retention set at 0.4 or 0.6 pound per cubic foot (pcf). Specimens were then kiln dried using schedules having maximum dry-bulb temperatures of either 160°, 190°, or 240° F. Edgewise static bending tests were then performed according to the ASTM Standard D 198. It was found that CCA treatments and redrying had no effect on the average modulus of elasticity (MOE), but they reduced average modulus of rupture (MOR), maximum load, maximum center span deflection, and work to maximum load up to 29% depending on level of treatment, method of redrying, strength ratio, and presence or absence of pith.

Gilfedder et al. (1968) studied the influence of certain preservatives on pole splitting. Poles of Eucalyptus oblica 6 to 9 m long were cut into specimens of 3 m length each. The top sections of the poles were salt-treated using the full-cell process, the butt sections creosote-treated using a standard Lowry process, and the mid-sections were used as a control. The tests were carried out during a five-year period. It was found that creosoted specimens split much less than salt treated or untreated specimens; and that the treatment of hardwood poles with waterborne preservatives did not appear to accentuate splitting compared with similar untreated poles.
Ethington (1972), studied the effect of preservative treatment on wood hardness. Matched section of kiln-dried and air-dried southern pine poles were treated with creosote, penta-petroleum, penta-volatile petroleum, CCA type C, or were left untreated. Hardness was measured according to ASTM D143-52. It was found that in all except for the air-dried creosote-treated group, the treated specimens averaged lower hardness than the matched control ones.

Kumar and Jain (1978) studied the effects of different salt loading CCA preservative on physical properties of wood. Defect-free, specimens of 7.5 x 2.5 x 1.25 cm of Pinus roxburghii (chir) and Mangifera indica (mango) were vacuum-treated (650 mm Hg) in a desiccator, using three different CCA concentrations. Four specimens of mango and 3 specimens of chir were salt treated at each concentration. Control groups consisting of the same number of specimens for each species were treated with water. For both species, at very low salt concentration, shrinkage and swelling values exceeded the respective values of control specimens, and reached maximum retention levels of 4 kg/m$^3$ for chir and 8 kg/m$^3$ for mango before falling gradually as the salt concentration was increased. The reason for this stabilization of the cell wall at high salt concentration may be due to the fact that more chemicals become available to cross-link with the cell wall substances. It is postulated that the trivalent chromium complexes formed during fixation are polynuclear, therefore stereochemically suited to cross-link with cellulose (Nicholas 1973).
Other theories of this stabilization of the cell wall are: (1) an increase in the number of hydroxyl groups caused by a rupture of linkages between cellulose-hemicellulose-lignin system, (2) a partial depletion of hemicellulose with acid solutions of the preserving salts (Kumar and Jain 1978).

1.3.8 Safety and Environmental Aspects of Wood Preservation

Pesticides, including wood preservatives are at the forefront of public concern about the effects of chemicals on health and the environment. From an environmental standpoint, wood preservatives differ from other pesticides in that the active ingredients are designated to persist in the wood for decades. They are not deliberately sprayed around or put onto food; environmental pollution or entry into the food chain occurs as a result of accident or improper disposal of waste, not as part of their improper normal use. However, in the case of developing countries such as Senegal, where literacy is low, and fuel wood is the main domestic energy, concerns of proper use and population information must be addressed.

Hilditch (1991) outlined some basic requirements addressing safety and environmental concerns: (1) the active ingredients must have low acute and chronic mammalian toxicity, and must not accumulate in the body; (2) they must be fixed in the wood sufficiently not to expose users of the wood or of wooden buildings or articles to harmful amounts either through direct contact or via the air. Since the solvent evaporates into the atmosphere, the work place must be sufficiently ventilated. Discharge of the solvent into the general atmosphere must be a main concern and other alternatives must be investigated.
MATERIAL AND PROCEDURES
2.1 Permeability and Pressure Impregnation

2.1.1 Species and Sampling Procedure

All the specimens used in this study were taken from *Casuarina equisetifolia* trees growing in the coastal plantations of Senegal. All the materials were provided by the Senegal Forest Service and were taken from 10 to 15 year-old trees. The material consisted of five logs of 1.5 meter long with butt diameters from 17 to 23 centimeters. Two logs were used for the preservation part of the study (log A and log B). Each log was cut into discs 15 cm length (disc 1 to 4 or 5). From each disc, dowels of 3/4 inch (1.9 cm) diameter were removed by means of a plugcutter.

Each log was divided into four parts labelled North (N), South (S), West (W), and East (E). Specimens were always cut starting at the location closest to the cambium layer working toward the pith, and numbered from 1 to 3 or 4 as they were being cut. Hence each specimen had a code comprised of two letters and two numbers. Example, specimen S1A3 is the first (1) specimen taken from the South section (S) of the third (3) disc of log A. Figure 2.1.1 gives the sampling procedure used in this study.
For example, if the formation of the heartwood had already started, the results would show higher permeability values for the outermost specimens. These specimens are more likely to be almost all sapwood. Accordingly, innermost specimens would yield lower permeability values. These specimens would be more likely to be composed of almost all heartwood. Since heartwood formation is an ongoing process starting at the pith boundary toward the cambium layer, specimens cut in the intermediary zone should show different permeability values.

Due to the rapid wearing of the plugcutter, some specimens had a very rough surface. Hence, all specimens were sanded with a sanding belt to get a smoother surface. The diameters were different however, and varied from 1.66 cm to 1.81 cm. The length also varied from 5.11 to 5.61 cm. A first set of specimens were oven-dried at 104 °C to constant weight. For almost all the oven-dried specimens a large number of checks were noticed. Therefore, a second set of specimens were conditioned at 12% relative humidity to avoid, or at least decrease, the number of checks. Because of the presence of checks, knots, other defects, and the necessity to conserve the initial distribution across the discs, the final sample size consisted of 60 specimens.
The weight (g), diameter (cm), and volume (cm$^3$) of each specimen were taken at 0 and 12% moisture content for oven-dried and room conditioned specimens respectively. For the relatively check-free oven-dried specimens, the dry specific gravity (0% MC) was computed directly from the ratio of the dry weight to the dry volume, since in the metric system dry specific gravity is numerically equal to density at 0% moisture content. For room conditioned specimens, the dry weight of each specimen was computed from its weight at 12% moisture content using Equation [2.1.1].

$$\text{Weight}_{0\%} = \frac{\text{Weight}_{12\%}}{1 + 0.12}$$  \[2.1.1\]

The specific gravity (G) at 12% moisture of each specimen was calculated according to Equation [2.1.2].

$$G_{12\%} = \frac{D_{12\%}}{(1 + 0.12) \rho}$$  \[2.1.2\]

where $G_{12\%} = \text{specific gravity at 12\% moisture content}$; $D_{12\%} = \text{Density of the wood at 12\% moisture content}$; $\rho = \text{the density of water}$.

The dry specific gravity of each specimen was computed based on Equation [2.1.3].

$$G_2 = \frac{G_1}{1 + 0.01G_1(m_{c_2} - m_{c_1})}$$  \[2.1.3\]
Replacing $G_2$ by $G_{12\%}$ and $G_1$ by $G_{0\%}$ and solving for $G_{0\%}$

$$G_{0\%} = \frac{G_{12\%}}{1 - (G_{12\%} \cdot 0.01mc_{12\%})} \quad [2.1.4]$$

The porosity of each specimen was calculated based on Equation [2.1.5]

$$V_a = 1 - G (0.667 + 0.01 M) \quad [2.1.5]$$

### 2.1.2 Parameters and Experimental Design

**Permeability Measurements**

The apparatus used in this study was of simple design and was comprised of a vacuum pump, two pressure gauges reading from zero to 760 mmHg, a 3/4" rubber tube of 10 cm long, a flowmeter, and a needle valve.

Gauge 1 gives the vacuum after the specimen in mmHg, and gauge 2 gives the vacuum before the specimen. The absolute pressures $P_1$ and $P_2$ are obtained by subtracting the readings of the vacuum gauges from the atmospheric pressure. The pressure difference across the specimen is obtained by subtracting $P_1$ from $P_2$; and the mean pressure $\bar{P}$ is given, by Equation [2.1.6].

$$\bar{P} = \frac{P_1 + P_2}{2} \quad [2.1.6]$$
The superficial air permeability of each specimen was calculated based on Equation [2.1.7].

\[ k_s = \frac{760 \ Q \ L \ P_s}{A \ \Delta P \ \bar{P}} \quad [2.1.7] \]

where 760 is the conversion factor from mmHg to atmospheres, \( Q \) is the rate of air passing through the wood specimen in cm\(^3\) /s, \( L \) is the specimen length cm, \( P_s \) is the barometric pressure in mmHg, \( \Delta P \) is the pressure drop across the specimen in mmHg, \( A \) is the cross-sectional area of the specimen in cm\(^2\), \( \bar{P} \) is the mean pressure in mmHg, \( k_s \) is the longitudinal air permeability expressed in cm\(^3\) (air) / s cm atm. Figure 2.1.2 shows the apparatus used for permeability measurements.
Figure 2.1.2: Apparatus of Permeability Measurements
Determination of Vessel size and distribution

Since open vessels are the primary flow path in hardwoods, longitudinal air permeability determined from permeability measurements (Equation 2.1.7) should give a good match with permeability determined from anatomical vessel measurements (Equation 1.2.6).

For the determination of vessel size and number, one specimen with a cross-section of 5 x 5 m with a thickness of 0.5 mm was randomly cut from each of the three locations given in 2.1.2 for permeability measurements. A square box of 400 x 400 microns was superposed to each specimen and the box was moved over the entire cross-section. At each location, the number of vessels present inside the box were counted, before a different square was covered. There was no overlap between the different squares, and inside each square the number of vessel-fractions was counted. If an entire vessel was present inside a square, its mean diameter was computed by averaging its largest and smallest chords.

Preservation Treatment

Specimens whose permeability were measured were full-cell treated with a zinc chloride solution at 1% concentration. In order to determine the effect of impregnation pressure on solution retention, impregnation pressures of 1, 2, 4, and 8 atmospheres were applied at different schedules. One schedule consisted of a complete treatment cycle at each impregnation pressure. A treatment cycle is composed of: 30 minutes vacuum, cylinder filled under vacuum, pressure applied for one hour.

Material and Procedures
Sixteen specimens were randomly selected from each permeability class. Half (24) of the specimens were end-coated, and the other half were side-coated using a five-minute epoxy. Twelve specimens (4 for each permeability class) were treated at each impregnation pressure. In each permeability class, specimens were divided in four groups, one for each impregnation pressure. In each group of four specimens two were end-coated, and the other two were side-coated. Therefore, each coating group was composed of 24 specimens, six for each permeability class. Table 2.1.1 gives the sample selection method.
### Table 2.1.1: Sampling Method for Impregnation

<table>
<thead>
<tr>
<th>Pressure</th>
<th>1 atm</th>
<th>2 atm</th>
<th>4 atm</th>
<th>8 atm</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>End-Coat</td>
<td>2 2 2</td>
<td>2 2 2</td>
<td>2 2 2</td>
<td>2 2 2</td>
<td>24</td>
</tr>
<tr>
<td>Side-Coat</td>
<td>2 2 2</td>
<td>2 2 2</td>
<td>2 2 2</td>
<td>2 2 2</td>
<td>24</td>
</tr>
<tr>
<td>Total</td>
<td>4 4 4</td>
<td>4 4 4</td>
<td>4 4 4</td>
<td>4 4 4</td>
<td>48</td>
</tr>
</tbody>
</table>
Prior to each treating schedule, the weight and volume of each specimen were determined, before and after coating. The location where the diameter of each specimen was measured was marked, so that the diameter after impregnation could be measured at that same place. This would avoid measurement errors that would happen if a same diameter was taken at two different location, given that the specimens were not perfectly round.

For each specimen the weight of the coating was calculated by subtracting the weight before coating from the weight after coating. The net weight of the each specimen after treatment was then obtained by subtracting the weight of the coating from the weight after treatment. The weight gain for each specimen was obtained by subtracting the net weight before treatment from the net weight after treatment.

The solution retention (Ret.) for each specimen was calculated based on Equation [2.1.8]

\[
\text{Ret.} = \frac{\Delta W_i}{V_1} \frac{g}{cc}
\]  

[2.1.8]

where Ret. is the solution retention in g/cm³, \( \Delta W_i \) is the weight gain during the impregnation process in g, \( V_1 \) is the volume of the wood before impregnation in cm³.
The fraction of voids filled by the preservative solution ($F_{vl}$) (which is also another way of expressing preservative retention) is given by Equation [2.1.9].

$$F_{vl} = \frac{W_u}{\rho V_a V_1}$$  \[2.1.9\]

where $W_u$ is the weight gain during the impregnation process taking into consideration the moisture content of the wood before impregnation; $\rho$ is the density of the preserving solution; $V_a$ is the porosity of the wood specimen before impregnation; $V_1$ is the volume of the wood before impregnation.
RESULTS AND DISCUSSION
3.1 Permeability

As shown earlier, Darcy's law was used to calculate the longitudinal air permeability of *Casuarina equisetifolia*. It was not possible to differentiate sapwood from heartwood based on visual observation such as color differences. The major source of variation for permeability was the location of the specimens across the discs.

An analysis of variance was done to determine if the three permeability classes are significantly different at the 5% level, using Duncan's Multiple Range test. The test did in fact show that permeability values for the three different locations across the discs were significantly different. The observed F statistic ($F_{\text{obs}}$) was equal to 351.65 while $F_{2,571,0.05}$ is about equal to 3.17. The results of permeability measurements are given in Table 3.1.1.
Table 3.1.1: Permeability Results*

<table>
<thead>
<tr>
<th>Class</th>
<th>N</th>
<th>Mean</th>
<th>Std Dev.</th>
<th>Min</th>
<th>Max.</th>
<th>95% Conf. Int. for Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>16</td>
<td>1009</td>
<td>403</td>
<td>392</td>
<td>1662</td>
<td>794</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1224</td>
</tr>
<tr>
<td>Medium</td>
<td>23</td>
<td>2544</td>
<td>3666</td>
<td>1881</td>
<td>3182</td>
<td>2386</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2702</td>
</tr>
<tr>
<td>High</td>
<td>21</td>
<td>4373</td>
<td>394</td>
<td>3638</td>
<td>4990</td>
<td>4193</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4552</td>
</tr>
<tr>
<td>Total</td>
<td>60</td>
<td>2775</td>
<td>1385</td>
<td>392</td>
<td>4990</td>
<td>2417</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3133</td>
</tr>
</tbody>
</table>

* The units are expressed in cm$^3$(air)/cm s atm.
In each permeability class, four specimens were randomly chosen, and four air permeability (kg) measurements were done for each. The specimen was left inside the specimen holder, and the air flow controlled with the needle valve. The mean permeability of each specimen was obtained by averaging the four measurements.

3.2 Vessel size and Number

An average of 1830 vessel elements per cm² was determined for *Casuarina*, with a mean diameter of about 117 microns or 0.0117 centimeters. Vessel lumens did not show any presence of tyloses.

Since permeability depends on the size and number of pore openings, a comparison between the experimental superficial air permeability from measurements and the calculated theoretical permeability obtained from measurements of vessel size (r) and number (n) would give some insight into the level of agreement between these two methods.

A theoretical permeability value of 4710 cm³/(air) / cm s atm was computed based on Equation [1.2.6]. Recall that the maximum longitudinal air permeability determined from permeability measurements was 4990 cm³/(air)/cm s atm. Therefore, there is an agreement between the experimental longitudinal air permeability values and the theoretical permeability of *Casuarina* obtained from vessel measurements.

If the theoretical air permeability of 4710 cm³/cm s atm is expressed in cm³/(air) cm/dyne s and replaced in Equation 1.2.7, the volume fraction of vessels of 0.2 is obtained for *Casuarina* wood. Due to their size, almost all the longitudinal
flow goes through the vessels. Table 3.1.2 presents the results for vessel measurements, and Figure 3.1.1 shows a cross-sectional cut of *Casuarina*. 
### Table 3.1.2: Vessel Number and Size

<table>
<thead>
<tr>
<th>Chord</th>
<th>Mean (micron)</th>
<th>Std Dev (micron)</th>
<th>Variance (micron$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smallest</td>
<td>99</td>
<td>22</td>
<td>506</td>
</tr>
<tr>
<td>Largest</td>
<td>135</td>
<td>30</td>
<td>921</td>
</tr>
<tr>
<td>Average</td>
<td>117</td>
<td>32</td>
<td>1022</td>
</tr>
<tr>
<td>Vessel Number</td>
<td>1830 / cm$^2$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.1.1: Cross-Section of Casuarina's Wood
In summary, the following conclusions can be drawn from the permeability measurements of *Casuarina*:

- *Casuarina equisetifolia* presents about 1830 vessel elements per square centimeter with an average diameter of 117 microns.

- there is a distinct variability in longitudinal air permeability between corewood (inner specimens) and sapwood (outer specimens),

- there is a good agreement between the maximum superficial longitudinal air permeability and theoretical permeability computed from anatomical measurements made on *Casuarina*. 
3.2 Pressure Impregnation

The importance of preservative penetration in the transverse direction (either radial or tangential) is of primary concern in wood preservation. If the preservative solution is not able to move from one cell to the adjacent one because of the wood's structure, the chemicals may not be able to accomplish their role of protection. This becomes a determinant factor for products such as utility poles which are designed to be used in contact with the ground. It was not possible to determine preservative penetration for side-coated specimens since they were completely impregnated. Therefore, only transverse penetration was determined.

The role of impregnation pressure on preservative penetration and solution retention was investigated for each permeability class at the 5% confidence level. The difference between permeability classes relative to preservative penetration and solution retention was also investigated at the 5% level.

For side-coated specimens, in addition to the effect of impregnation pressure on solution retention, the relationship between solution retention and longitudinal air permeability was investigated. The results from the impregnation process are shown in appendix A for end-coated and side-coated specimens respectively.

3.2.1 End-Coated Specimens

1. **Effects of Impregnation Pressure on Preservative Penetration**

The analysis of variances showed that the linear relationship between impregnation pressure and preservative penetration is not significant at the 5% level for the low permeability class ($F_{obs} = 2.80$) and barely significant for the high permeability class ($F_{obs} = 6.40$) with an $F_{1,610.95} = 5.99$. The same relationship is
significant for medium permeability specimens ($F_{\text{obs.}} = 16.18$) and can be expressed by Equation [3.2.1].

$$Penetration = 0.131 + 0.033 \, P \, (\text{medium permeability})$$ [3.2.1]

where $P =$ the impregnation pressure in atm.

Duncan's-MR test was done at the 5% level to determine whether these differences in preservative penetration were statistically significant. When all the mean penetrations were cross-compared, they were not significantly different from each other (Table 3.2.1).
Table 3.2.1: Comparison of Mean Preservative Penetrations

<table>
<thead>
<tr>
<th>Source</th>
<th>D.F.</th>
<th>SS</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>2</td>
<td>.0108</td>
<td>.0054</td>
</tr>
<tr>
<td>Within Groups</td>
<td>21</td>
<td>.1766</td>
<td>.0084</td>
</tr>
<tr>
<td>Total</td>
<td>23</td>
<td>.1874</td>
<td></td>
</tr>
</tbody>
</table>

\[
F_{\text{obs}} = .64 \quad F_{12,210.05} = 3.47 \quad F_{\text{tab.}} = .53
\]

<table>
<thead>
<tr>
<th>Class</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>Std</td>
<td>.060</td>
<td>.110</td>
<td>.090</td>
<td>.080</td>
</tr>
<tr>
<td>Mean</td>
<td>.240</td>
<td>.280</td>
<td>.210</td>
<td>.240</td>
</tr>
</tbody>
</table>

* Penetration units are in centimeter
The results in Table 3.2.1 indicate that medium permeability specimens show the highest penetration values, followed by the low permeability specimens, and then the higher permeability ones. Recall that these permeability classes are longitudinal air permeability while here transverse penetration was measured. Therefore, impregnation pressure can be considered as the most important variable in predicting transverse preservative penetration. At a given pressure, the three permeability classes are not significantly different in relation to preservative penetration. When all specimens are combined together, the relationship between impregnation pressure and preservative penetration was significant at the 5% confidence level ($F_{\text{obs.}} = 20.78$ and $F_{(1, 22)}^{0.95} = 4.30$). It is expressed by Equation [3.2.2].

$$Penetration = 0.149 + 0.023 \, P \ (\text{Average Penetration})$$  \[3.2.2\]

where $P$ is the impregnation pressure in atm.

Table 3.2.2 give the results of the analyses of variance for preservative penetration.
## Table 3.2.2: Effects of Impregnation Pressure on Preservative Penetration

<table>
<thead>
<tr>
<th>Permeability</th>
<th>Low</th>
<th>Medium</th>
<th>High(^1)</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N)</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>(F) statistics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(F_{\text{obs}})</td>
<td>2.80</td>
<td>16.18</td>
<td>6.40</td>
<td>20.78</td>
</tr>
<tr>
<td>(F_{(1,60.95)})</td>
<td>5.99</td>
<td>5.99</td>
<td>5.99</td>
<td>4.30</td>
</tr>
<tr>
<td>(P)-value</td>
<td>0.145</td>
<td>0.007</td>
<td>0.045</td>
<td>0.000</td>
</tr>
<tr>
<td>(R^2)</td>
<td>0.21</td>
<td>0.68</td>
<td>0.44</td>
<td>0.48</td>
</tr>
<tr>
<td>Std Error</td>
<td>0.050</td>
<td>0.063</td>
<td>0.073</td>
<td>0.006</td>
</tr>
<tr>
<td>Intercept</td>
<td>0.202</td>
<td>0.131</td>
<td>0.114</td>
<td>0.149</td>
</tr>
<tr>
<td>Slope</td>
<td>0.011</td>
<td>0.033</td>
<td>0.024</td>
<td>0.023</td>
</tr>
</tbody>
</table>

\* The units are expressed in centimeter

\(^1\) It was decided to accept the null hypothesis for the high permeability class, due to the fact the relationship is barely significant at the 5% level.
In general, the following conclusions can be drawn:

- There is a significant linear relationship between the pressure used to force a preservative solution into a given wood and how far the solution will travel inside the wood.

- Equation [3.2.2] can be used to predict the transverse penetration depth of a water-borne preservative in a *Casuarina*’s wood at a given impregnation pressure.

Figures 3.2.1 to 3.2.4 give the regression prediction lines for preservative penetration for low, medium, high, and for all end-coated specimens.
Penetration = .202 + .011 P

Figure 3.2.1: Penetration vs Pressure Low Permeability
End-Coated Specimens

note: Each circle represents one observation. If there is two or more observations laying very close to each other, a line is drawn from the center of the circle outward.
Figure 3.2.2: Penetration vs Pressure Medium Permeability
End-Coated Specimens

note: Each circle represents one observation. If there is two or more observations laying very close to each other, a line is drawn from the center of the circle outward.
Figure 3.2.3: Penetration vs Pressure High Permeability

End-Coated Specimens

note: Each circle represents one observation. If there is two or more observations laying very close to each other, a line is drawn from the center of the circle outward.

Penetration = .114 + .024 P

F obs = 6.04
F .95 = 5.99
P-value = .045
Adj. Rsq = .44
Penetration = 0.149 + 0.023 P

Impregnation Pressure (atm)

Preservative Penetration (cm)

Figure 3.2.4: Penetration vs Pressure
All End-Coated Specimens

note: Each circle represents one observation. If there are two or more observations lying very close to each other, a line is drawn from the center of the circle outward.

F obs = 20.78
F .95 = 4.30
P-value = .000
Adj. Rsq = .46
2. **Effects of Impregnation Pressure on Solution Retention**

The analyses of variance showed that the linear relationship between impregnation pressure and solution retention is not significant at the 5% confidence level for the low \( (F_{\text{obs}} = 4.06) \) and medium \( (F_{\text{obs}} = 4.47) \) permeability classes, with an \( F_{1.09} = 5.39 \). However, the same linear relationship is significant for high permeability specimens \( (F_{\text{obs}} = 15.13) \). This relationship for high permeability specimens is expressed by Equation [3.2.3].

\[
\text{Retention} = 0.159 + 0.013P \quad (\text{high permeability}) \quad [3.2.3]
\]

where \( P \) is the impregnation pressure in atm.

When all the end-coated specimens are analyzed together regardless of their permeability classes, the linear relationship between impregnation pressure and solution retention was very significant at the 5% confidence level \( (F_{\text{obs}} = 15.03 \) and \( F_{1.22} = 4.30 \). This relationship can be expressed using Equation [3.2.4].

\[
\text{Retention} = 0.168 + 0.014P \quad (\text{average retention}) \quad [3.2.5]
\]

where \( P \) is the impregnation pressure in atm.

Duncan's-MR test was also done at the 5% level to determine whether the mean retentions of the three permeability classes are statistically different. The results are given in table 3.2.3.
Table 3.2.3: Comparison of Mean Retentions for End-Coated Specimens

<table>
<thead>
<tr>
<th>Source</th>
<th>D.F.</th>
<th>SS</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>2</td>
<td>.0054</td>
<td>.0027</td>
</tr>
<tr>
<td>Within Groups</td>
<td>21</td>
<td>.0780</td>
<td>.0037</td>
</tr>
<tr>
<td>Total</td>
<td>23</td>
<td>.0835</td>
<td></td>
</tr>
</tbody>
</table>

\[ F_{\text{obs}} = .73 \quad F_{0.05(2,21)} = 3.47 \quad F_{\text{havb}} = .49 \]

<table>
<thead>
<tr>
<th>Class</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>Std</td>
<td>.085</td>
<td>.043</td>
<td>.045</td>
<td>.060</td>
</tr>
<tr>
<td>Mean</td>
<td>.242</td>
<td>.211</td>
<td>.210</td>
<td>.221</td>
</tr>
</tbody>
</table>
Table 3.2.3 indicates that low permeability specimens have the highest solution retention, followed by medium and high permeability ones. These last two classes did show almost the same mean retentions. The mean retentions are not significantly different from one permeability class to the other at 5% confidence level. Table 3.2.4 shows the analyses of variance of solution retention for end-coated specimens. Figures 3.2.5 to 3.2.8 show the regression prediction lines for the low, medium, high permeability classes, and for all the end-coated specimens.
### Table 3.2.4: Effects of Pressure on Retention for End-Coated Specimens

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>N</strong></td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td><strong>F Statistics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{obs} = 4.06$</td>
<td>$F_{obs} = 4.47$</td>
<td>$F_{obs} = 15.13$</td>
<td>$F_{obs} = 15.03$</td>
<td></td>
</tr>
<tr>
<td>$F_{1,60.95} = 5.99$</td>
<td>$F_{1,60.95} = 5.99$</td>
<td>$F_{1,60.95} = 5.99$</td>
<td>$F_{1,229.95} = 4.30$</td>
<td></td>
</tr>
<tr>
<td>P-value = .09</td>
<td>P-value = .079</td>
<td>P-value = .008</td>
<td>P-value = .0008</td>
<td></td>
</tr>
<tr>
<td><strong>Adj. R$^2$</strong></td>
<td>.30</td>
<td>.33</td>
<td>.67</td>
<td>.38</td>
</tr>
<tr>
<td><strong>Std Error</strong></td>
<td>.050</td>
<td>.035</td>
<td>.026</td>
<td>.047</td>
</tr>
<tr>
<td><strong>Intercept</strong></td>
<td>.172</td>
<td>.174</td>
<td>.159</td>
<td>.168</td>
</tr>
<tr>
<td><strong>Slope</strong></td>
<td>.019</td>
<td>.01</td>
<td>.013</td>
<td>.014</td>
</tr>
</tbody>
</table>
Figure 3.2.5: Retention vs Pressure Low Permeability
End-Coated Specimens
Figure 3.2.6: Retention vs Pressure Medium Permeability

End-Coated Specimens

Retention = .174 + .01 P

F_{obs} = 4.47
F .95 = 5.99
P-value = .079
Adj. Rsq = .33

note: Each circle represents one observation. If there is two or more observations laying very close to each other, a line is drawn from the center of the circle outward.
Figure 3.2.7: Retention vs Pressure High Permeability
End-Coated Specimens
Retention = .168 + .014 P

F obs = 15.03
F .95 = 4.30
P-value = .0008
Adj. Rsq = .38

Figure 3.2.8: Retention vs Pressure
All End-Coated Specimens

note: Each circle represents one observation. If there is two or more observations laying very close to each other, a line is drawn from the center of the circle outward.
3.2.2 Side-Coated Specimens

1. Effects of Impregnation Pressure on Solution Retention for Side-Coated Specimens

The linear relationship between Impregnation pressure and solution retention for low \( (F_{obs} = 25.65) \), and high permeability specimens \( (F_{obs} = 15.7) \) was very significant at the 5% confidence level \( (F_{1,60.95} = 5.99) \). The relationship between the two variables can be expressed using Equations [3.2.6] and [3.2.7] for low and high permeability specimens respectively. This was not the case for medium permeability specimens, for which the linear relationship was barely significant \( (F_{obs} = 5.58) \).

\[
Ret. = 0.366 + 0.023P \quad (low \: permeability) \quad [3.2.6]
\]

\[
Ret. = 0.48 + 0.019P \quad (high \: permeability) \quad [3.2.7]
\]

where \( P \) is the impregnation pressure in atm.

Mean retention of the three permeability classes were compared at the 5% level using Duncan’s MR test. The results of the test are given in Table 3.2.5.
Table 3.2.5: Comparison Solution Retention for Side-Coated Specimens

<table>
<thead>
<tr>
<th>Source</th>
<th>D.F.</th>
<th>SS</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>2</td>
<td>.0444</td>
<td>.0222</td>
</tr>
<tr>
<td>Within Groups</td>
<td>21</td>
<td>.0891</td>
<td>.0042</td>
</tr>
<tr>
<td>Total</td>
<td>23</td>
<td>.1336</td>
<td></td>
</tr>
</tbody>
</table>

\[
F_{\text{vbr}} = 5.23 \quad F_{\text{12,210.55}} = 3.47 \quad F_{\text{nvbr}} = .014
\]

<table>
<thead>
<tr>
<th>Class</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>Std</td>
<td>.074</td>
<td>.055</td>
<td>.065</td>
<td>.076</td>
</tr>
<tr>
<td>Mean</td>
<td>.454</td>
<td>.535</td>
<td>.552</td>
<td>.514</td>
</tr>
<tr>
<td>Low*</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*the stars indicate significant difference between groups
The results shown in Table 3.2.5 indicate that for side-coated specimens, solution retention increases proportionally to permeability and that low permeability specimens are significantly different from the medium and high ones relative to the amount of preservative intake. These last two permeability specimens (medium and high) are not significantly different from each other.

Therefore, it seems logical to divide side-coated specimens into two retention groups, one group composed of low permeability specimens only (group 1), and the other group composed of medium and high permeability classes combined together (group 2). The linear relationship between solution retention and impregnation pressure was then investigated for group 2, since the relationship is already known for group 1.

When combined, the linear relationship between impregnation pressure and solution for medium and high permeability specimens becomes more significant than for any group considered alone (\( F_{\text{obs}} = 19.99 \) and \( F_{1,14|0.95} = 4.6 \)). This relationship can be expressed using Equation [3.2.8].

\[
\text{Retention} = 0.48 + 0.016P \quad (\text{group 2}) \tag{3.2.8}
\]

where \( P \) is the impregnation pressure in atm.

However, it would be more practical to have a single equation expressing solution retention as a function of impregnation pressure for all side-coated specimens. In general, the permeability of the wood is not determined prior to its impregnation. For this reason, solution retention of all 24 side-coated specimens
was investigated at the 5% level.

When all side-coated specimens are combined, the linear relationship between impregnation pressure and solution retention is also very significant regardless of permeability classes ($F_{\text{obs}} = 17.85$ and $F_{1.22;0.95} = 4.30$). This relationship can be expressed using Equation [3.2.9].

\[
\text{Retention} = 0.444 + 0.019P \quad (\text{average retention}) \quad [3.2.9]
\]

where $P$ is the impregnation pressure in atm.

Tables 3.2.6 shows the results of the different analysis of variance for side-coated specimens. Figures 3.2.9 to 3.2.13 represent the regression prediction lines for low, medium, high permeability classes, group 2 permeability specimens, and for all side-coated specimens respectively.
Table 3.2.6: Effects of Impregnation Pressure on Solution Retention for Side-Coated Specimens

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>Medium*</th>
<th>High</th>
<th>Medium/High</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>16</td>
<td>24</td>
</tr>
<tr>
<td>F Statistics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{obs} = 25.65$</td>
<td>$F_{obs} = 5.98$</td>
<td>$F_{obs} = 15.7$</td>
<td>$F_{obs} = 19.99$</td>
<td>$F_{obs} = 17.85$</td>
<td></td>
</tr>
<tr>
<td>$F_{1,80.95} = 5.99$</td>
<td>$F_{1,80.95} = 5.99$</td>
<td>$F_{1,80.95} = 5.99$</td>
<td>$F_{1,140.95} = 4.8$</td>
<td>$F_{1,220.95} = 4.30$</td>
<td></td>
</tr>
<tr>
<td>P-value = .002</td>
<td>P-value = .06</td>
<td>P-value = .007</td>
<td>P-value = .000</td>
<td>P-value = .000</td>
<td></td>
</tr>
<tr>
<td>Adj. $R^2$</td>
<td>.78</td>
<td>.39</td>
<td>.88</td>
<td>.56</td>
<td>.42</td>
</tr>
<tr>
<td>Std Error</td>
<td>.035</td>
<td>.043</td>
<td>.036</td>
<td>.039</td>
<td>.058</td>
</tr>
<tr>
<td>Intercept</td>
<td>.366</td>
<td>.48</td>
<td>.48</td>
<td>.48</td>
<td>.444</td>
</tr>
<tr>
<td>Slope</td>
<td>.023</td>
<td>.013</td>
<td>.019</td>
<td>.016</td>
<td>.019</td>
</tr>
</tbody>
</table>

* It was decided to accept the null hypothesis for the high permeability class, due to the fact the relationship is barely significant at the 5% level.
Figure 3.2.9: Retention vs Pressure Low Permeability
Side-Coated Specimens

Retention = .366 + .023 P

F_{obs} = 25.65
F_{.95} = 5.99
P-value = .002
Adj Rsq = .78

Note: Each circle represents one observation. If there is two or more observations laying very close to each other, a line is drawn from the center of the circle outward.
Retention = 0.48 + 0.013 P
F obs = 5.58
F .95 = 5.99
P value = .06
Adj R sq = .39

Figure 3.2.10: Retention vs Pressure Medium Permeability Side-Coated Specimens
Figure 3.2.11: Retention vs Pressure High Permeability
Side-Coated Specimens

Retention = 0.48 + 0.019 P

Fobs = 15.7
F.95 = 5.99
P-value = 0.007
Adj Rsq = 0.68

Note: Each circle represents one observation. If there is two or more observations laying very close to each other, a line is drawn from the center of the circle outward.
Retention = .48 + .016 P

Fobs = 19.99
F .95 = 4.6
P-value = .0008
Adj Rsq = .56

Figure 3.2.12: Retention vs Pressure Side-Coated Medium and High Permeability Classes

note: Each circle represents one observation. If there is two or more observations laying very close to each other, a line is drawn from the center of the circle outward.
Figure 3.2.13: Retention vs Pressure
All Side-Coated Specimens

note: Each circle represents one observation. If there is two or more observations laying very close to each other, a line is drawn from the center of the circle outward.
2. **Effects of Permeability on Solution Retention for Side-Coated Specimens**

Solution retention was plotted against longitudinal air permeability at each of the four impregnation pressures. Since the flow of both fluids (air and preservative solution) did occur in the longitudinal direction, the amount of preservative intake should increase according to the longitudinal air permeability.

At the 5% confidence level the linear relationship is not significant at impregnation pressures of 1 atm ($F_{\text{obs}} = 3.09$) and 2 atm ($F_{\text{obs}} = 6.55$) where $F_{(1,4),0.05} = 7.71$. However, at 4 and 8 atmospheres the linear relationship was very significant $F_{\text{obs}} = 17.15$ and $F_{\text{obs}} = 11.24$ respectively (Equations 3.2.10 and 3.2.11).

\[
\text{Ret.} = 0.451 + 3.807 \times 10^{-5} \text{kg} \quad \text{(at 4 atm.)} \quad [3.2.10]
\]

\[
\text{Ret.} = 0.519 + 2.504 \times 10^{-5} \text{kg} \quad \text{(at 8 atm.)} \quad [3.2.11]
\]

where kg is the longitudinal air permeability expressed in cm$^2$(air)/cm s atm. Figure 3.2.14 shows the different regression prediction lines at each impregnation pressure.
Figure 3.2.14: Effects of Permeability on Retention

1 atm: $F_{obs} = 3.09$  Adj $R^2 = 0.29$
2 atm: $F_{obs} = 6.55$  Adj $R^2 = 0.53$
4 atm: $F_{obs} = 17.15$  Adj $R^2 = 0.76$
8 atm: $F_{obs} = 11.24$  Adj $R^2 = 0.67$
Using Duncan's-MR test at the 5% confidence level, the different impregnation pressures were compared to each other with regard to the amount of solution retention. The results of the test showed that solution retention increases in relation to longitudinal air permeability for a given pressure. This confirmed therefore the primary role of permeability on the amount of preservative intake. Solution retention at 1 and 2 atm are not significantly different. Four and eight atmospheres impregnation pressures are also not significantly different with regard to solution retention. However, 1 and 2 atm are significantly different from 4 and 8 atm relative to the amount of preservative intake. These results suggest that there is no difference in the amount of solution retention whether the wood is pressure treated at 1 or 2 atm. The same thing can also be said between 4 and 8 atmospheres. Since a solution retention target is always set prior to the impregnation process, more research should be done in this area to investigate the economical efficiency of various impregnation pressures. Table 3.2.7 shows the results of the comparison of the different mean retention with regard to the different impregnation pressures.
Table 3.2.7: Comparison of Mean Retention per Impregnation Pressure for Side-Coated Specimens

<table>
<thead>
<tr>
<th>Source</th>
<th>D.F.</th>
<th>SS</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>3</td>
<td>.0657</td>
<td>.0219</td>
</tr>
<tr>
<td>Within Groups</td>
<td>20</td>
<td>.0678</td>
<td>.0034</td>
</tr>
<tr>
<td>Total</td>
<td>23</td>
<td>.1336</td>
<td></td>
</tr>
</tbody>
</table>

\[ F_{obs} = 8.46 \quad F_{0.05,20} = 3.10 \quad F_{0.05} = .0031 \]

<table>
<thead>
<tr>
<th>Pressure</th>
<th>1 atm</th>
<th>2 atm</th>
<th>4 atm</th>
<th>8 atm</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td>Std</td>
<td>.065</td>
<td>.054</td>
<td>.068</td>
<td>.042</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>.458</td>
<td>.468</td>
<td>.545</td>
<td>.583</td>
<td></td>
</tr>
</tbody>
</table>

1 atm
2 atm
4 atm
8 atm

* indicates significant difference between variables
Based on the results obtained from the mean comparison, the impregnation pressures were divided into two groups: group A composed of 1 and 2 atm, and group B composed of 4 and 8 atm. The linear relationships were significant for both groups $F_{obs} = 10.03$ and $F_{obs} = 10.03$ for group A and B respectively ($F_{1,10|0.05} = 4.96$) at the 5% level (Equations [3.2.12] and [3.2.13]). Recall that the same relationship was not significant for either of the two impregnation pressures composing group A.

$$\text{Ret.} = 0.401 + 2.53 \times 10^{-5} \text{kg (group A)} \quad [3.2.12]$$

$$\text{Ret.} = 0.482 + 3.269 \times 10^{-5} \text{kg (group B)} \quad [3.2.13]$$

where kg is the longitudinal air permeability expressed in cm$^3$(air)/cm s atm.

The linear relationship between longitudinal air permeability and solution retention for all side-coated specimens, regardless of the impregnation pressure was also significant at the 5% level ($F_{obs} = 11.09$ $F_{1,22|0.05} = 4.30$ Adj. $R^2 = .30$). It is expressed by Equation [3.2.14].

$$\text{Ret.} = 0.44 + 2.94 \times 10^{-5} \text{kg (average retention)} \quad [3.2.14]$$

where kg is the longitudinal air permeability expressed in cm$^3$(air)/cm s atm.
Equation [3.2.15] expresses the relationship between solution retention and the Log of permeability, which is also significant at the 5% confidence level $F_{\text{obs}} = 16.64$ and $F_{110.95} = 4.3$.

\[ \text{Retention} = 0.018 + 0.065 \log kg \ (\text{for } \log kg) \]  \hspace{1cm} [3.2.15]

where Log kg is the logarithmic of longitudinal air permeability in $\text{cm}^3(\text{air})/\text{cm} \ \text{s} \ \text{atm}$.

In conclusion it has been shown that:

- at a given impregnation pressure, solution retention increases relative to longitudinal air permeability,
- in general, this relationship can be expressed by Equation [3.2.14],
- Equation [3.2.15] can be used to express solution retention in function of the logarithm of longitudinal air permeability,
- there is not a significant difference at a given solution retention target if the impregnation pressure is between 1 and 2 atm; or between 4 and 8 atm. This last point is rather important for cost considerations.

Table 3.2.8 gives the results of the analysis of variance for group A and B, and for all side-coated specimens, and Figures 3.2.15, 3.2.16, and 3.2.17 give their respective regression prediction lines.
Table 3.2.8: Retention and Longitudinal Air Permeability for Side-Coated Specimens

<table>
<thead>
<tr>
<th></th>
<th>Group A 1 &amp; 2 atm</th>
<th>Group B 4 &amp; 8 atm</th>
<th>kg</th>
<th>Log kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>12</td>
<td>12</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>F Statistics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F_{obs} = 10.03</td>
<td>F_{obs} = 22.11</td>
<td>F_{obs} = 11.09</td>
<td>F_{obs} = 16.64</td>
<td></td>
</tr>
<tr>
<td>F_{I,100,95} = 4.96</td>
<td>F_{I,100,95} = 4.96</td>
<td>F_{II,210,95} = 4.2</td>
<td>F_{II,210,95} = 4.3</td>
<td></td>
</tr>
<tr>
<td>P-value = .01</td>
<td>P-value = .0008</td>
<td>P-value = .003</td>
<td>P-value = .0005</td>
<td></td>
</tr>
<tr>
<td>Adj. R²</td>
<td>.45</td>
<td>.66</td>
<td>.30</td>
<td>.40</td>
</tr>
<tr>
<td>Std Error</td>
<td>.042</td>
<td>.034</td>
<td>.063</td>
<td>.059</td>
</tr>
<tr>
<td>Intercept</td>
<td>.401</td>
<td>.482</td>
<td>.44</td>
<td>.018</td>
</tr>
<tr>
<td>Slope</td>
<td>2.53x10^5</td>
<td>3.29x10^5</td>
<td>2.94x10^5</td>
<td>.085</td>
</tr>
</tbody>
</table>
Retention = 0.401 + 2.53 E(-5) kg

Fobs = 10.03
F.95 = 4.96
P-value = .01
Adj Rsq = .45

Figure 3.2.15: Retention vs kg
Pressures of 1 and 2 atm

Note: Each circle represents one observation. If there is two or more observations
laying very close to each other, a line is drawn from the center of the circle outward.
Retention = 0.482 + 3.269 E(-5) kg

Fobs = 22.11
F .95 = 4.96
P-value = .0008
Adj Rsq = .66

Longitudinal Air Permeability [cc(air)/cm s atm]

Figure 3.2.16: Retention vs kg
Pressures 4 and 8 atm

note: Each circle represents one observation. If there is two or more observations laying very close to each other, a line is drawn from the center of the circle outward.
\text{Retention} = 0.44 + 2.94 \times 10^{-5} \text{ kg}

\begin{align*}
\text{F}_{\text{obs}} &= 11.09 \\
F_{.95} &= 4.3 \\
P\text{-value} &= .003 \\
\text{Adj Rsq} &= .30
\end{align*}

Figure 3.2.17: Retention vs kg All Side-Coated Specimens
Retention = 0.018 + 0.065 Log kg

F_{obs} = 16.64
F_{.95} = 4.3
P-value = 0.0005
Adj Rsq = 0.40

Figure 3.2.18: Retention vs Log kg All Side-Coated Specimens
3.3 Mechanical Characteristics of *Casuarina*

Static bending tests were done to determine the mechanical properties of *Casuarina*. Twenty-two specimens were tested according to ASTM 143 secondary methods, the load applied at mid-span. Prior to testing, the specimens were conditioned at 12% moisture content. The load at elastic limit $P_1$ was determined visually from the load-deflection curves. Appendix B gives the results for all specimens.

The modulus of rupture for each specimen was derived based on Equation [3.3.1].

$$MOR = \frac{1.5 \ P_1}{bh^2} \times 10^{-2}$$  \[3.3.1\]

where $MOR =$ modulus of rupture in MegaPascal (MPa); $P =$ the maximum load in Newton (N); $l =$ length of the span in cm; $b =$ the width and $h =$ the height of the specimen in cm.

In addition to the modulus of rupture, values were also derived for fiber stress at elastic limit ($r$). In calculating $r$ the same formula is used as for $MOR$, except that the load at elastic limit ($P_1$) is substituted for the maximum load ($P$).

The modulus of elasticity (MOE) for each specimen was computed based on Equation [3.3.2].
\[ MOE = \frac{P_1 l^3}{4 Dbh^3} \times 10^{-2} \]  

[3.3.2]  

where \( MOE = \) modulus of elasticity in MPa; \( P_1 = \) load at or below elastic limit in Newton; \( D = \) deflection produced by \( P_1 \); and \( b \) and \( h \) are the same than in Equation [3.3.1]. The work to elastic limit or elastic resilience \( (S) \) was computed from Equation [3.3.3].

\[ S = \frac{P_1 D}{2V} \]  

[3.3.3]  

where \( S = \) work to elastic limit in N/cm\(^2\); \( V = \) volume of the specimen between supports; \( D \) is the same as defined in the previous equations. \( S \) is an expression of the amount of work that can be applied repeatedly under a given loading without deforming permanently the specimen. The results are summarized in Table 3.3.1.
Table 3.3.1: Results of Static Bending Test with Load Applied at Mid-Span

<table>
<thead>
<tr>
<th>Variable*</th>
<th>Mean</th>
<th>Std Dev</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>D (cm)</td>
<td>.390</td>
<td>.04</td>
<td>.102</td>
</tr>
<tr>
<td>MOE (MPa)</td>
<td>13,194</td>
<td>1,381.00</td>
<td>.105</td>
</tr>
<tr>
<td></td>
<td>12,617**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOR (MPa)</td>
<td>108</td>
<td>7.87</td>
<td>.073</td>
</tr>
<tr>
<td></td>
<td>147**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P (N)</td>
<td>3,097</td>
<td>217.02</td>
<td>.070</td>
</tr>
<tr>
<td>P, (N)</td>
<td>1,741</td>
<td>187.37</td>
<td>.108</td>
</tr>
<tr>
<td>r (MPa)</td>
<td>61</td>
<td>6.65</td>
<td>.109</td>
</tr>
<tr>
<td>S (N/cm²)</td>
<td>4</td>
<td>.70</td>
<td>.174</td>
</tr>
</tbody>
</table>

* D is the total deflection at elastic limit in cm; MOE is the modulus of elasticity in MPa; MOR is the modulus of rupture in MPa; P is the maximum load in Newton; P, is the load at elastic limit in Newton; r is the fiber stress at elastic limit in MPa; S is elastic resilience or work to elastic limit in N/cm².

** the second set of data are taken from Chudnoff (1984). They are based on 2-cm standard at 12% moisture content.
To use *Casuarina* as electric poles in Senegal, its maximum stress at a given load must be within the acceptable limits for the Standards NF C67-100. Equation [3.3.5] was therefore used to determine the ultimate stress at ground line (R).

\[
R = \frac{4P}{\pi r^3} \tag{3.3.5}
\]

where \( R \) = maximum stress at ground line in MPa; \( P \) = the carrying load of the pole, given in Table 1.1.1; \( l \) = the length of the pole between the ground line and the point at which the load is applied in mm; \( r \) = the radius of the pole at ground line in mm.

The values obtained from Equation [3.3.5] would be indicative of the theoretical strength properties of a *Casuarina* beam. These results were then compared to MOR determined from small clear specimens used in this study. Recall that the mean MOR and MOE obtained 108 and 13,194 MPa respectively. Based on Equation [3.3.5], the largest stress at ground line for the different classes of electric poles used in Senegal is about 51 MPa. Recall that the carrying loads given in Table 1.1.1 includes safety factors such as: (1) a maximum stress at the ground line, which should be at least less than one-third of the predefined breaking stress of 55 MPa; and (2) a wind load up to 5.3 \( 10^4 \) MPa.

Table 3.3.2 gives the maximum stress at ground line for electric poles derived from Equation [3.3.5]; the MOR and MOE values are those obtained from small clear specimens of 1" x 1" (2.5 x 2.5 cm) conditioned at 12% moisture content.
Table 3.3.2: Maximum Stress at Ground line for the Different Classes of Electric Poles Used in Senegal

<table>
<thead>
<tr>
<th>Pole Type</th>
<th>Pole length (m)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9</td>
<td>10</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Theoretical Maximum Stress at Ground line (MPa)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S140</td>
<td>50</td>
<td>49</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>S255</td>
<td>50</td>
<td>49</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>S325</td>
<td>50</td>
<td>49</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>S430</td>
<td>51</td>
<td>49</td>
<td>48</td>
<td></td>
</tr>
</tbody>
</table>

Average Modulus of Rupture from Small Clear Specimens (MPa)

108
Thus, the use of *Casuarina* trees in Senegal as utility poles appears to be safe, given the strength properties of the wood determined in this study. However, to determine the suitability of *Casuarina* as utility poles its behavior under full length poles must be studied. Such behavior would be influenced by wood defects such as knots, grain angle, juvenile wood any other growth characteristics that may influence in one way or another the mechanical properties of wood. For the discussion concerning the effects of wood characteristics on its mechanical properties, the reader is referred to Bodig and Jayne (1982) or to any wood mechanics book.

3.4 Economic Aspects of a Local Production of Utility Poles in Senegal

In 1990, the annual importation of telephone and electric poles was estimated of about 10,000 and 15,000 poles respectively (Moreno 1990). The unit cost for telephone and electric poles was estimated at more than 57,000 CFA and 85,000 CFA respectively. These cost figures have almost doubled since the devaluation of the CFA in January 1994. Each year more than one billion CFA ($ 2 million US) worth of utility poles are imported. In 1992, the potential production of *Casuarina* electric poles was estimated by Ndiaye (1992b) based on the Standards NF C67-100. Table 3.3.3 gives the results of the inventory.
Table 3.4.1: Estimation of Supply of *Casuarina* electric poles

<table>
<thead>
<tr>
<th>Station</th>
<th>Total Area Planted (Ha)</th>
<th>Area Inventoried (Ha)</th>
<th>Total Poles Inventoried</th>
<th>Avg Poles per Ha inventoried</th>
<th>Potential No. of Poles</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>1,705</td>
<td>415</td>
<td>1,085</td>
<td>2.61</td>
<td>4,450</td>
</tr>
<tr>
<td>Center</td>
<td>3,263</td>
<td>644</td>
<td>12,175</td>
<td>18.90</td>
<td>61,670</td>
</tr>
<tr>
<td>South</td>
<td>4,634</td>
<td>1,545</td>
<td>2,735</td>
<td>1.80</td>
<td>8,341</td>
</tr>
<tr>
<td>Total</td>
<td>9,602</td>
<td>2,604</td>
<td>15,995</td>
<td></td>
<td>74,461</td>
</tr>
</tbody>
</table>

Source: Ndiaye 1992b

* *Casuarina* plantations are subdivided in three stations.
The figures in Table 3.4.1 give the current estimated number of poles (15,995), and the potential number of poles for all the plantations (74,461). If fifteen years is taken as the average mature age for a *Casuarina* tree, and at that age the tree must be cut and replaced, an average of 4,964 poles can therefore be produced annually. This potential annual production should however, be revised downward due to the fact that the plantations are subdivided into three bands. The first band closest to the water front has a major role of protection, thus can be submitted to a selective cutting only. The band at rear line is the production band and will furnish much of the poles. The band in between these two plays a protection role as well as production role and should also be submitted to a selective cutting. It has been estimated that it would cost nearly 250 CFA ($0.41) to cut, clean, and transport a fresh pole log to a distance of 15 Km from the harvesting site (Ndiaye 1992b).

The potential supply of utility poles is much greater for teak plantations. It has been estimated that an average of more than 10,000 teak poles (2,984 electric poles and 7,422 telephone poles) can be obtained for a period of 40 years (Gueye 1984). These numbers should be revised upward due to the fact that the first cuts were scheduled in 1985 and have never been done. Since a field trial of teak electric poles had already been conducted satisfactorily (Gueye 1984), this species can therefore be considered as a supplementary source of supply even though any technical study relative to its suitability hasn’t been done yet. Gueye (1984) estimated that the total cost of processing a teak pole from the plantation site to a treatment facility located at about 50 km, would be:
- 14,136 CFA ($ US 24) for an electric pole
- 7,698 CFA ($ US 13) for a telephone pole

Even if a total inflation of 100% between 1985 and 1994 is adopted, a locally produced pole would cost 28,272 CFA ($ US47) and 15,396 ($ US 26) for electric and telephone poles respectively. Table 3.4.2 gives the after devaluation cost for utility poles and the adjusted estimated cost of locally produced poles.
Table 3.4.2: Estimated Cost after Devaluation of Imported Poles and Average Cost of Locally Produced Poles

<table>
<thead>
<tr>
<th>SENELEC</th>
<th>SONATEL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Imported Poles</strong></td>
<td><strong>Imported Poles</strong></td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td><strong>CFA franc</strong></td>
</tr>
<tr>
<td><strong>S 140</strong></td>
<td>95,492</td>
</tr>
<tr>
<td><strong>160</strong></td>
<td><strong>$ US</strong></td>
</tr>
<tr>
<td><strong>S 255</strong></td>
<td>100,332</td>
</tr>
<tr>
<td><strong>169</strong></td>
<td><strong>$ US</strong></td>
</tr>
<tr>
<td><strong>S 325</strong></td>
<td>127,832</td>
</tr>
<tr>
<td><strong>213</strong></td>
<td><strong>$ US</strong></td>
</tr>
<tr>
<td><strong>S 430</strong></td>
<td>170,928</td>
</tr>
<tr>
<td><strong>285</strong></td>
<td><strong>$ US</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Locally produced poles</strong></th>
<th><strong>Locally produced poles</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>28,272</td>
<td>15,396</td>
</tr>
<tr>
<td>47</td>
<td>25</td>
</tr>
</tbody>
</table>

* The adjusted costs of imported poles in CFA was calculated by doubling the price before devaluation, even though the inflation rate is currently about 50%.

** The CFA figures are converted in $ US which are given in the second set of data: $ US 1 = 6 French Franc = 600 CFA
From Table 3.4.2 it becomes easy to understand the constant pressure exerted by the utility companies toward the Senegal Forest Service in order to use local species for their supply. The use of both teak and *Casuarina* plantations can reduce to almost an insignificant level the imports of utility poles.
SUMMARY

The suitability of *Casuarina equisetifolia* trees grown in Senegal as utility poles was assessed by determining the treatability of the species, and the mechanical properties of the wood with regard to the requirements of the Standards for utility poles in the country. Since teak plantations have always been thought as a major supply source of utility poles, this species was also included in the analysis.

In the first part of the study, the longitudinal air permeability of 60 specimens of *Casuarina equisetifolia* trees from Senegal, was measured with the flowmeter method. It was not possible to differentiate sapwood from heartwood based on the color of the wood. The permeability values were then divided into three classes (high, medium and low permeabilities). This classification matched perfectly the location of each specimen across the discs. Specimens from the outermost part of the discs showed high permeability values. The lowest permeabilities were found in the specimens located nearest to the pith.

An average of 1830 vessels per cm$^2$ was found for *Casuarina*. The vessels of *Casuarina* did not seem to be completely plugged. The mean diameter of the vessels was 117 microns. A theoretical permeability of 4710 cm$^3$/cm s atm was found while the highest permeability value determined in the experiment was 4990 cm$^3$(air)/cm s atm. These two values show a good agreement between theoretical permeability of *Casuarina* and its experimental longitudinal air permeability. The volume fraction of vessels of 0.20 derived from the theoretical permeability indicates that these elements, because of their large size represent the main flow path of the wood.
In the second part of the study, a total number of forty-eight specimens (half end-coated and half side-coated) were pressure treated with a 1% Zinc Chloride treating solution, using a full-cell process at absolute pressures of 1, 2, 4, and 8 atmospheres. Transverse and longitudinal preservative penetration were investigated by coating half of the specimens at both ends, and the other half around the circumference, using a five-minute epoxy. All the possible regressions between penetration, retention, and pressure and permeability were done at the 5% confidence level. For both methods of coating, a significant linear relationship was found between retention and pressure. One and two atmosphere impregnation pressures were not significantly different relative to retention. The same thing was also found for 4 and 8 atm. The most important variables that determine the effectiveness of the treating process were the impregnation pressure and the permeability of the specimen.

Lastly, static bending tests were conducted on 22 small clear specimens of size 1" x 1" x 16" (2.5 x 2.5 x 40.64 cm). The load was applied at mid-span length 14" (35.56 cm). An average of 108 and 13,194 MPa were obtained for modulus of rupture and modulus of elasticity respectively. The theoretical maximum stress at ground line of a pole was computed for each of the different classes of pole used in Senegal. These theoretical maximum stresses at ground line varied between 46 and 51 MPa. The ratio MOR to maximum stress at ground line varied between 2.12 to 2.34. This high ratio indicates that Casuarina trees have the strength properties required for utility poles, and therefore can be used for that purpose.
CONCLUSION

The results of this study showed that *Casuarina equisetifolia* trees grown in Senegal possess the physical and mechanical properties necessary for its use as utility poles in Senegal. In addition to *Casuarina* plantations, teak plantations can also be used for the same purpose. These two species can nearly ensure a regular supply of the country's need in utility poles.

During the first part of the study, the treatability of *Casuarina* was investigated by first determining its permeability and then treating the wood at different absolute impregnation pressures with a 1% Zinc Chloride solution using a full-cell process. Sosa and Hesse (1989) obtained 100% retention of *Casuarina*’s sapwood and 60% for heartwood using the same process at an absolute pressure of about 10 atm. In this study an average fraction of voids filled of .79 (79% of the voids of the wood were filled by the preserving solution) was obtained at an absolute pressure of 8 atm. Recall that the distinction between sapwood and heartwood could not be made in the specimens used in this study.

The mechanical properties of the species show enough strength in the wood to meet the requirements of the Standard NF C67-100 and NF C11-201, which set the guidelines for the use of electric and telephone poles respectively in Senegal. Allied with *Casuarina* plantations, the use of teak plantations would allow the country to nearly satisfy its needs in utility poles or at least bring to an insignificant level the imports of utility poles. However, prior to any large scale production of *Casuarina* poles the following should be done:

1. The Boucherie process should be used to treat a limited number of poles to
evaluate penetration retention and properties of a full length pole. These properties would certainly differ from those determined from small samples. The Boucherie method is easy to implement, cheap, and gives good results. It is very suited to the Senegalese conditions where labor is available and not expensive. Another advantage of the process is that *Eucalyptus* and teak poles can also be treated with the same process. The use of the Boucherie process doesn’t, however, exclude the implementation of more modern treatment methods. This process would constitute a transition phase during which a local expertise in full scale treatment of utility poles can be developed, not only for *Casuarina* poles but also for teak and *Eucalyptus* poles.

2. A field performance evaluation of the treated poles should be done to determine the efficiency of the preservative system and the behavior of the treated pole.

3. In addition, a mechanical test of full length poles should be done. Strength properties determined from small clear specimens do not take into considerations growth factors such as knots, grain angle, juvenile wood which play an important role in assessing the mechanical properties of a full length pole.

Conclusion
APPENDIX A1: Pressure Impregnation Results for End-Coated Specimens*

<table>
<thead>
<tr>
<th>PC</th>
<th>P (atm)</th>
<th>Vol (cc)</th>
<th>WG (g)</th>
<th>Ret. (g/cc)</th>
<th>MR (g/cc)</th>
<th>Penet. (cm)</th>
<th>$k_s$</th>
<th>$F_{vl}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>1</td>
<td>12.68</td>
<td>2.84</td>
<td>0.22</td>
<td>0.0022</td>
<td>0.30</td>
<td>1308</td>
<td>0.39</td>
</tr>
<tr>
<td>Low</td>
<td>2</td>
<td>12.87</td>
<td>3.93</td>
<td>0.31</td>
<td>0.0031</td>
<td>0.20</td>
<td>437</td>
<td>0.56</td>
</tr>
<tr>
<td>Low</td>
<td>2</td>
<td>13.06</td>
<td>2.26</td>
<td>0.17</td>
<td>0.0017</td>
<td>0.25</td>
<td>949</td>
<td>0.29</td>
</tr>
<tr>
<td>Low</td>
<td>4</td>
<td>12.56</td>
<td>2.99</td>
<td>0.24</td>
<td>0.0024</td>
<td>0.20</td>
<td>1089</td>
<td>0.43</td>
</tr>
<tr>
<td>Low</td>
<td>4</td>
<td>12.94</td>
<td>2.61</td>
<td>0.20</td>
<td>0.0020</td>
<td>0.25</td>
<td>541</td>
<td>0.38</td>
</tr>
<tr>
<td>Low</td>
<td>8</td>
<td>13.23</td>
<td>3.27</td>
<td>0.25</td>
<td>0.0025</td>
<td>0.30</td>
<td>363</td>
<td>0.37</td>
</tr>
<tr>
<td>Low</td>
<td>8</td>
<td>12.57</td>
<td>5.20</td>
<td>0.41</td>
<td>0.0041</td>
<td>0.30</td>
<td>1194</td>
<td>0.74</td>
</tr>
<tr>
<td>Medium</td>
<td>1</td>
<td>12.42</td>
<td>2.07</td>
<td>0.17</td>
<td>0.0017</td>
<td>0.20</td>
<td>3182</td>
<td>0.22</td>
</tr>
<tr>
<td>Medium</td>
<td>1</td>
<td>13.19</td>
<td>2.71</td>
<td>0.21</td>
<td>0.0021</td>
<td>0.10</td>
<td>2517</td>
<td>0.28</td>
</tr>
<tr>
<td>Medium</td>
<td>2</td>
<td>12.57</td>
<td>2.65</td>
<td>0.21</td>
<td>0.0021</td>
<td>0.30</td>
<td>2003</td>
<td>0.28</td>
</tr>
<tr>
<td>Medium</td>
<td>2</td>
<td>13.26</td>
<td>1.98</td>
<td>0.15</td>
<td>0.0015</td>
<td>0.15</td>
<td>2994</td>
<td>0.23</td>
</tr>
<tr>
<td>Medium</td>
<td>4</td>
<td>13.08</td>
<td>3.54</td>
<td>0.27</td>
<td>0.0027</td>
<td>0.20</td>
<td>2168</td>
<td>0.37</td>
</tr>
<tr>
<td>Medium</td>
<td>4</td>
<td>12.94</td>
<td>2.31</td>
<td>0.18</td>
<td>0.0018</td>
<td>0.30</td>
<td>1887</td>
<td>0.26</td>
</tr>
<tr>
<td>Medium</td>
<td>8</td>
<td>12.70</td>
<td>3.22</td>
<td>0.25</td>
<td>0.0025</td>
<td>0.40</td>
<td>3028</td>
<td>0.32</td>
</tr>
<tr>
<td>Medium</td>
<td>8</td>
<td>12.92</td>
<td>3.20</td>
<td>0.25</td>
<td>0.0025</td>
<td>0.40</td>
<td>2001</td>
<td>0.31</td>
</tr>
<tr>
<td>High</td>
<td>1</td>
<td>12.96</td>
<td>2.80</td>
<td>0.22</td>
<td>0.0022</td>
<td>0.20</td>
<td>4472</td>
<td>0.27</td>
</tr>
<tr>
<td>High</td>
<td>1</td>
<td>12.85</td>
<td>2.17</td>
<td>0.17</td>
<td>0.0017</td>
<td>0.20</td>
<td>3957</td>
<td>0.25</td>
</tr>
<tr>
<td>High</td>
<td>2</td>
<td>12.97</td>
<td>2.02</td>
<td>0.16</td>
<td>0.0016</td>
<td>0.20</td>
<td>4088</td>
<td>0.21</td>
</tr>
<tr>
<td>High</td>
<td>2</td>
<td>12.82</td>
<td>2.32</td>
<td>0.18</td>
<td>0.0018</td>
<td>0.10</td>
<td>4081</td>
<td>0.25</td>
</tr>
<tr>
<td>High</td>
<td>4</td>
<td>12.98</td>
<td>2.45</td>
<td>0.19</td>
<td>0.0019</td>
<td>0.15</td>
<td>4439</td>
<td>0.28</td>
</tr>
<tr>
<td>High</td>
<td>4</td>
<td>12.64</td>
<td>2.60</td>
<td>0.21</td>
<td>0.0021</td>
<td>0.10</td>
<td>4411</td>
<td>0.28</td>
</tr>
<tr>
<td>High</td>
<td>8</td>
<td>13.02</td>
<td>3.38</td>
<td>0.26</td>
<td>0.0026</td>
<td>0.35</td>
<td>4158</td>
<td>0.37</td>
</tr>
<tr>
<td>High</td>
<td>8</td>
<td>12.43</td>
<td>3.62</td>
<td>0.29</td>
<td>0.0029</td>
<td>0.35</td>
<td>4454</td>
<td>0.41</td>
</tr>
</tbody>
</table>

*PC = the permeability class; Vol = volume of the specimen in cm³; WG = the weight gain of the specimen in g; MR = the mineral retention or fractional weight of dry salt retained by the specimen; $k_s$ = the longitudinal air permeability of the specimen in cm³(air)/cm s atm; and $F_{vl}$ = the fraction of voids filled by the preservative solution.
### APPENDIX A2: Pressure Impregnation Results for Side-Coated Specimens

<table>
<thead>
<tr>
<th>PC</th>
<th>P (atm)</th>
<th>Vol (cc)</th>
<th>WG (g)</th>
<th>Ret (g/cc)</th>
<th>M. R. (g/cc)</th>
<th>$k_g$</th>
<th>$F_{VL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>1</td>
<td>12.29</td>
<td>4.27</td>
<td>0.35</td>
<td>0.0035</td>
<td>504</td>
<td>0.53</td>
</tr>
<tr>
<td>Low</td>
<td>1</td>
<td>11.28</td>
<td>4.68</td>
<td>0.42</td>
<td>0.0042</td>
<td>759</td>
<td>0.77</td>
</tr>
<tr>
<td>Low</td>
<td>2</td>
<td>12.99</td>
<td>4.98</td>
<td>0.38</td>
<td>0.0038</td>
<td>917</td>
<td>0.72</td>
</tr>
<tr>
<td>Low</td>
<td>2</td>
<td>12.48</td>
<td>5.58</td>
<td>0.45</td>
<td>0.0045</td>
<td>683</td>
<td>0.71</td>
</tr>
<tr>
<td>Low</td>
<td>4</td>
<td>12.19</td>
<td>5.83</td>
<td>0.48</td>
<td>0.0048</td>
<td>564</td>
<td>0.92</td>
</tr>
<tr>
<td>Low</td>
<td>4</td>
<td>12.90</td>
<td>5.84</td>
<td>0.45</td>
<td>0.0045</td>
<td>1161</td>
<td>1.02</td>
</tr>
<tr>
<td>Low</td>
<td>8</td>
<td>12.69</td>
<td>7.36</td>
<td>0.58</td>
<td>0.0058</td>
<td>1390</td>
<td>0.91</td>
</tr>
<tr>
<td>Low</td>
<td>8</td>
<td>11.80</td>
<td>6.10</td>
<td>0.52</td>
<td>0.0052</td>
<td>744</td>
<td>0.87</td>
</tr>
<tr>
<td>Medium</td>
<td>1</td>
<td>12.80</td>
<td>6.83</td>
<td>0.54</td>
<td>0.0054</td>
<td>2616</td>
<td>0.80</td>
</tr>
<tr>
<td>Medium</td>
<td>1</td>
<td>13.09</td>
<td>6.23</td>
<td>0.48</td>
<td>0.0048</td>
<td>2506</td>
<td>0.63</td>
</tr>
<tr>
<td>Medium</td>
<td>2</td>
<td>12.79</td>
<td>5.80</td>
<td>0.45</td>
<td>0.0045</td>
<td>2028</td>
<td>0.62</td>
</tr>
<tr>
<td>Medium</td>
<td>2</td>
<td>12.63</td>
<td>6.40</td>
<td>0.51</td>
<td>0.0051</td>
<td>2303</td>
<td>0.80</td>
</tr>
<tr>
<td>Medium</td>
<td>4</td>
<td>12.21</td>
<td>6.57</td>
<td>0.54</td>
<td>0.0054</td>
<td>1838</td>
<td>0.94</td>
</tr>
<tr>
<td>Medium</td>
<td>4</td>
<td>13.55</td>
<td>7.95</td>
<td>0.59</td>
<td>0.0059</td>
<td>2591</td>
<td>0.74</td>
</tr>
<tr>
<td>Medium</td>
<td>8</td>
<td>12.88</td>
<td>7.09</td>
<td>0.55</td>
<td>0.0055</td>
<td>2001</td>
<td>0.87</td>
</tr>
<tr>
<td>Medium</td>
<td>8</td>
<td>12.22</td>
<td>7.54</td>
<td>0.62</td>
<td>0.0062</td>
<td>2970</td>
<td>0.84</td>
</tr>
<tr>
<td>High</td>
<td>1</td>
<td>12.96</td>
<td>6.06</td>
<td>0.47</td>
<td>0.0047</td>
<td>4750</td>
<td>0.64</td>
</tr>
<tr>
<td>High</td>
<td>1</td>
<td>13.26</td>
<td>6.47</td>
<td>0.49</td>
<td>0.0049</td>
<td>3951</td>
<td>0.66</td>
</tr>
<tr>
<td>High</td>
<td>2</td>
<td>12.24</td>
<td>6.04</td>
<td>0.49</td>
<td>0.0049</td>
<td>4389</td>
<td>0.74</td>
</tr>
<tr>
<td>High</td>
<td>2</td>
<td>13.39</td>
<td>7.12</td>
<td>0.53</td>
<td>0.0053</td>
<td>4359</td>
<td>0.72</td>
</tr>
<tr>
<td>High</td>
<td>4</td>
<td>11.74</td>
<td>7.29</td>
<td>0.62</td>
<td>0.0062</td>
<td>4640</td>
<td>0.84</td>
</tr>
<tr>
<td>High</td>
<td>4</td>
<td>12.57</td>
<td>7.41</td>
<td>0.59</td>
<td>0.0059</td>
<td>4009</td>
<td>0.83</td>
</tr>
<tr>
<td>High</td>
<td>8</td>
<td>13.05</td>
<td>7.87</td>
<td>0.80</td>
<td>0.0060</td>
<td>3895</td>
<td>0.91</td>
</tr>
<tr>
<td>High</td>
<td>8</td>
<td>12.31</td>
<td>8.16</td>
<td>0.63</td>
<td>0.0063</td>
<td>4451</td>
<td>0.83</td>
</tr>
</tbody>
</table>
## APPENDIX B: Static Bending Results

<table>
<thead>
<tr>
<th>No</th>
<th>Depth (cm)</th>
<th>Width (cm)</th>
<th>Weight (g)</th>
<th>V (cm³)</th>
<th>P (Newton)</th>
<th>P₁ (Newton)</th>
<th>D (cm)</th>
<th>MOR (MPa)</th>
<th>MOR (MPa)</th>
<th>S (N/cm²)</th>
<th>r (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.47</td>
<td>2.47</td>
<td>169.33</td>
<td>85.86</td>
<td>2,661.14</td>
<td>1,334.47</td>
<td>0.3851</td>
<td>93</td>
<td>10,945</td>
<td>2.84</td>
<td>47</td>
</tr>
<tr>
<td>2</td>
<td>2.58</td>
<td>2.41</td>
<td>161.86</td>
<td>87.39</td>
<td>3,060.38</td>
<td>1,555.89</td>
<td>0.3334</td>
<td>101</td>
<td>12,633</td>
<td>2.97</td>
<td>52</td>
</tr>
<tr>
<td>3</td>
<td>2.44</td>
<td>2.43</td>
<td>176.71</td>
<td>93.24</td>
<td>2,895.79</td>
<td>1,556.86</td>
<td>0.3493</td>
<td>106</td>
<td>14,116</td>
<td>4.27</td>
<td>57</td>
</tr>
<tr>
<td>4</td>
<td>2.49</td>
<td>2.44</td>
<td>179.62</td>
<td>85.24</td>
<td>2,980.31</td>
<td>1,445.67</td>
<td>0.3175</td>
<td>105</td>
<td>15,540</td>
<td>2.69</td>
<td>51</td>
</tr>
<tr>
<td>5</td>
<td>2.48</td>
<td>2.42</td>
<td>198.41</td>
<td>84.44</td>
<td>2,601.14</td>
<td>1,578.12</td>
<td>0.3969</td>
<td>94</td>
<td>11,989</td>
<td>3.71</td>
<td>56</td>
</tr>
<tr>
<td>6</td>
<td>2.55</td>
<td>2.38</td>
<td>177.58</td>
<td>85.41</td>
<td>2,869.10</td>
<td>1,556.89</td>
<td>0.3651</td>
<td>98</td>
<td>12,033</td>
<td>3.33</td>
<td>53</td>
</tr>
<tr>
<td>7</td>
<td>2.50</td>
<td>2.44</td>
<td>189.92</td>
<td>85.79</td>
<td>3,015.89</td>
<td>1,568.08</td>
<td>0.3651</td>
<td>105</td>
<td>13,366</td>
<td>3.55</td>
<td>56</td>
</tr>
<tr>
<td>8</td>
<td>2.48</td>
<td>2.44</td>
<td>214.57</td>
<td>84.80</td>
<td>3,411.79</td>
<td>1,990.49</td>
<td>0.3810</td>
<td>121</td>
<td>14,963</td>
<td>4.25</td>
<td>67</td>
</tr>
<tr>
<td>9</td>
<td>2.54</td>
<td>2.43</td>
<td>187.92</td>
<td>86.53</td>
<td>3,042.58</td>
<td>1,779.19</td>
<td>0.3810</td>
<td>103</td>
<td>13,166</td>
<td>3.82</td>
<td>60</td>
</tr>
<tr>
<td>10</td>
<td>2.49</td>
<td>2.47</td>
<td>200.65</td>
<td>86.30</td>
<td>3,171.58</td>
<td>1,934.98</td>
<td>0.3969</td>
<td>110</td>
<td>14,291</td>
<td>4.45</td>
<td>67</td>
</tr>
<tr>
<td>11</td>
<td>2.55</td>
<td>2.44</td>
<td>194.50</td>
<td>87.33</td>
<td>3,300.58</td>
<td>1,957.22</td>
<td>0.3969</td>
<td>111</td>
<td>13,668</td>
<td>4.45</td>
<td>66</td>
</tr>
<tr>
<td>12</td>
<td>2.49</td>
<td>2.44</td>
<td>195.33</td>
<td>85.50</td>
<td>3,300.58</td>
<td>2,023.94</td>
<td>0.4266</td>
<td>116</td>
<td>13,971</td>
<td>5.07</td>
<td>71</td>
</tr>
<tr>
<td>13</td>
<td>2.50</td>
<td>2.41</td>
<td>186.50</td>
<td>84.52</td>
<td>3,073.72</td>
<td>1,957.22</td>
<td>0.4128</td>
<td>108</td>
<td>14,106</td>
<td>4.78</td>
<td>69</td>
</tr>
<tr>
<td>14</td>
<td>2.52</td>
<td>2.43</td>
<td>192.48</td>
<td>86.28</td>
<td>3,260.55</td>
<td>1,846.01</td>
<td>0.3810</td>
<td>112</td>
<td>13,338</td>
<td>4.08</td>
<td>63</td>
</tr>
<tr>
<td>15</td>
<td>2.48</td>
<td>2.43</td>
<td>195.72</td>
<td>84.90</td>
<td>3,287.24</td>
<td>1,990.49</td>
<td>0.3910</td>
<td>117</td>
<td>14,923</td>
<td>4.25</td>
<td>67</td>
</tr>
<tr>
<td>16</td>
<td>2.49</td>
<td>2.44</td>
<td>209.88</td>
<td>85.88</td>
<td>3,211.82</td>
<td>1,890.49</td>
<td>0.4604</td>
<td>112</td>
<td>12,075</td>
<td>5.08</td>
<td>66</td>
</tr>
<tr>
<td>17</td>
<td>2.46</td>
<td>2.51</td>
<td>202.35</td>
<td>87.19</td>
<td>3,456.27</td>
<td>1,890.49</td>
<td>0.3969</td>
<td>119</td>
<td>13,963</td>
<td>4.30</td>
<td>65</td>
</tr>
<tr>
<td>18</td>
<td>2.41</td>
<td>2.42</td>
<td>198.67</td>
<td>82.12</td>
<td>3,276.34</td>
<td>1,779.29</td>
<td>0.3869</td>
<td>123</td>
<td>14,725</td>
<td>4.30</td>
<td>67</td>
</tr>
<tr>
<td>19</td>
<td>2.55</td>
<td>2.43</td>
<td>186.00</td>
<td>86.87</td>
<td>3,193.82</td>
<td>1,712.57</td>
<td>0.3493</td>
<td>108</td>
<td>13,633</td>
<td>3.44</td>
<td>58</td>
</tr>
<tr>
<td>20</td>
<td>2.42</td>
<td>2.48</td>
<td>189.75</td>
<td>84.36</td>
<td>2,908.14</td>
<td>1,712.57</td>
<td>0.4783</td>
<td>106</td>
<td>11,425</td>
<td>4.83</td>
<td>63</td>
</tr>
<tr>
<td>21</td>
<td>2.49</td>
<td>2.42</td>
<td>192.78</td>
<td>84.71</td>
<td>3,042.58</td>
<td>1,558.88</td>
<td>0.4921</td>
<td>108</td>
<td>9,467</td>
<td>4.52</td>
<td>55</td>
</tr>
<tr>
<td>22</td>
<td>2.47</td>
<td>2.45</td>
<td>188.68</td>
<td>85.25</td>
<td>3,069.27</td>
<td>1,779.29</td>
<td>0.3869</td>
<td>108</td>
<td>13,468</td>
<td>4.14</td>
<td>63</td>
</tr>
</tbody>
</table>
REFERENCES

American Society for Testing Materials (ASTM) 1990. Section 4 Volume 04.09 Wood

American Wood Preservers’ Association Standards 1983


Nostrand Reinhold, New York.

Choong, E.T., McMillin C.W., Tesoro F.O. 1975. Effect of the surface preparation on the


Chudnoff, Martin. 1984. Tropical timbers of the world. US Forest Service, Agricultural
Handbook # 607.

Forest Products Journal 17(10):41-46.

Côté, W.A. Jr. 1958. Electron microscope studies of pit membrane structure: implications in

Adjustment. Praeger, N.Y.

Journal 22 (5) : 60-62

Publishers.

Journal 18(1) 28-30

Gueye, S. 1984. Possibilities de Production de Poteaux de Ligne à partir des plantations de


Blacksburg, Virginia.


References


CURRICULUM VITAE

of

Babacar S. Gueye

September 1994

Business Address

Dept. of Wood Science and Forest Products

1650 Ramble Rd., Blacksburg, Virginia 24061-0503

Home Address

Eaux et Forêts B.P 1831

Dakar, Senegal

Personal

Born January 6, 1960

Education

Diploma in Forest Projects Management - 1990 Bamako, Republic of Mali

Diploma in Small Business Management - 1989 University of Pittsburgh, Pittsburgh, PA

Diploma-Junior Engineer - 1986 Ecole Nationale des Cadres Ruraux de Bambey

Major: Forestry

Baccalaureat Natural Science - 1980 University of Dakar, Dakar, Senegal