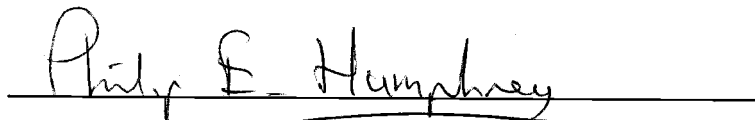AN ABSTRACT OF THE THESIS OF

<u>Shan Ren</u> for the degree of <u>Doctor of Philosophy</u> in

<u>Forest Products</u> presented on <u>September 27, 1991.</u>

Title: <u>Thermo-Hygro Rheological Behavior of Materials Used</u>

<u>in the Manufacture of Wood-Based Composites</u>

Abstract approved _____

Dr. Philip E. Humphrey

Thermo-hygro-rheology of wood-adhesive systems plays an important role during the hot pressing process of wood based composites. The principal objective of this research is to quantitatively study the thermo-hygro rheological characteristics of wood-adhesive systems used in such composites. This is with a view to providing material characteristics which may be used in simulation models of industrial hot pressing operations.

For this purpose, a specially designed miniature hot press system mounted on a servo-hydraulic testing machine was used to compress pre-formed fiber networks. The environment for each test was maintained uniform throughout the specimen by pre-treating it inside the system until the desired conditions of temperature and moisture were achieved.

Experiments have been conducted under a range of test conditions of load (1 to 6 MPa), temperature (25 °C to 150 °C) and moisture content (0% to 16%). A five-element rheological model has been developed, and the rheological constants of materials have been determined by incorporating the experimental results in the model.

Each element has been nonlinearly related to prevailing density (rather than stress) of the material. Over almost all of the investigated combinations of temperature and MC, increasing temperature and moisture leads to increased elastic, viscous, delayed elastic and plastic-fractural deformations at given load levels.

The results may aid in the optimization of existing products and the development of new ones.

Thermo-Hygro Rheological Behavior

of Materials Used in the

Manufacture of Wood-Based Composites

by

Shan Ren

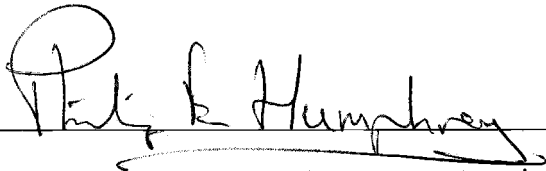A THESIS

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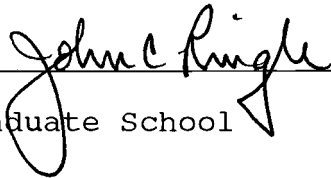
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ACKNOWLEDGEMENTS

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CHAPTER 1. INTRODUCTION

Thermo-hygro-rheology of wood-adhesive systems used in
structural composites plays an important role in determining
optimum process schedules for hot pressing. It also affects
structures and associated properties of the final products.
However, hot pressing is a complicated process. The wood-
adhesive system (wood: fibers, flakes or particles;
adhesives, and interface) simultaneously and continuously
sustains physical and chemical changes. Most of these vary
throughout the composite during hot pressing. Rheological
behavior (which includes elastic, delayed elastic, viscous,
plastic and micro-fractural types of mechanism) varies
depending upon the structure and properties of the material
and the localized thermodynamic conditions that occur within
the product as hot pressing progresses. Temperature and
moisture interactively affect these processes.

Both recoverable and permanent types of deformation
occur at various stages of the pressing process. The
deformations are effected by many physical factors, and the
rheological behavior in turn affects the entire physical
system (including mechanisms such as heat and moisture
transfer, and adhesion).

A fundamental understanding and the ability to make quantitative predictions of the rheological behavior of wood-adhesive systems during hot pressing are increasingly demanded for the development and improvement of high quality products. This is necessary in order to completely understand, effectively design and precisely control both the wood-adhesive system and the hot pressing process.

A study of the rheological behavior of wood-adhesive furnish materials under highly controlled conditions of load, temperature and moisture were conducted to characterize the rheological phenomena of wood composite furnish material. The principal objective of this research was to establish a quantitative understanding of the elastic, plastic, visco and micro-fracture types of behavior of the systems under the ranges of conditions that occur during hot pressing. Such understanding (material models) may be incorporated within simulation models which account for the interaction of rheology, thermodynamics (heat and moisture transfer with phase change) and adhesion in the hot pressing process. The models will ultimately be used as tools for product development and process optimization.

The following constituent objectives were established for the project:

1. To apply the concepts of rheology to study the characteristics of wood composite furnish materials under

diverse thermo-hygro (temperature and adsorbed moisture) condition.

2. To establish a model representing the thermo-hygro-rheological characteristics of the wood furnish materials under compression.

3. To develop new experimental techniques for determining rheological properties (the main focus of the work) and experimentally verifying the thermo-hygro-rheological model.

4. To provide rheological constants of wood composite materials in order to permit simulation of industrial pressing operations (incorporation of rheological behavior in a global three dimensional simulation model).

5. To provide a better understanding of the nature of the thermo-hygro-rheological behavior of wood-adhesive systems during hot pressing.

To realize the objectives of this research, new techniques were developed to offer a direct and automated means for investigating physical phenomena that occur during compression of furnish materials. For this purpose, specimens were tested under a range of accurately controlled steady-state conditions of temperature and moisture content. A specially designed test system capable of applying dynamic force in a highly controlled way were developed. This consisted of a miniature hot press system which was mounted

on a computer controlled servo-hydraulic testing machine.
Environments for each test were maintained constant and
uniform throughout the specimen by pre-treating it inside
the system until the desired conditions of temperature and
moisture were achieved. Desired experimental test conditions
were maintained constant during the subsequent test cycle by
controlling the temperature and water vapor pressure of the
atmosphere inside the sealed pressing system.

Experiments were conducted under a range of test
conditions (in particular load, temperature and equilibrium
moisture content). Information about strain and stress
versus time were derived from each selected combination of
compression pressure, temperature and moisture content.

Development of the above experimental techniques was
the principal objective of the research. However, a non-
linear five-element rheological model has also been
developed as a preliminary attempt to describe the
rheological characteristics of wood-adhesive systems. The
rheological constants of materials were therefore determined
from the experimental results. The rheological behavior and
the effects of temperature and moisture content may then be
characterized.

The first part of this thesis reviews rheological
concepts and applications, and the main physical aspects of
wood composites manufacturing are outlined. Then, the
research strategy is fully described. Fundamental issues in

structure analysis, rheological behavior and computational implications during hot pressing are briefly discussed. Efforts to understand and numerically reproduce hygro-thermo-rheological behavior are contemplated. Following the literature and background discussion, the methods for quantifying the rheological constants of composite materials from experimental data are developed. Next the experimental methods, test equipment and materials are described. The fourth part of the thesis concerns data analysis and computation. It is here that rheological constants are actually quantified. Then, the application of the five-element rheological model is considered.

The results of the research may aid in our understanding of the underlying mechanisms that affect rheological behavior of wood furnish materials at each stage during hot pressing. Innovations in experimental techniques and numerical methods of simulation are enabling us to develop effective models and experimental techniques which may prove to be useful tools. This research may motivate further study of the rheological mechanisms that occur during hot pressing.

CHAPTER 2. LITERATURE REVIEW

2.1. Introduction

As one of the important engineering materials, wood
composites are receiving increasing attention. The
continuous improvement of quality and performance of wood-
based composites and the efficient utilization of the wood
and other natural fiber materials from the renewable natural
resources continuously stimulate the development of wood-
based composite materials. This interest has, however, only
recently occurred as attempts to study the materials
fundamentally. Before that, trial and error methods were
used.

Traditional products such as wood composites face many
serious demands on its quality and performance. The
improvement and development of new wood composite materials
require more fundamental understanding and higher
engineering performance standards.

Thermo-hygro-rheology is an important aspect for
effectively designing and precisely controlling both the
structure and manufacturing (hot pressing) processes.
However, hot pressing is a complicated process. It involves
simultaneous physical and chemical changes within the wood-
adhesive systems. Most mechanisms occur differentially
throughout the composite during hot pressing and they

directly or indirectly effect the rheological behavior. The
main physical processes may be classified into the following
main areas (Humphrey, 1982; Humphrey and Bolton, 1985,
1989a):

    ---- thermo-hygro-rheological behavior of the wood-
        adhesive system (time-dependent densificaiton and
        stress relaxation).

    ---- adhesive polymerization and adhesion.

    ---- heat and moisture transfer (with phase change)
        within the wood-adhesive system.

These processes, as well as the structure of the
materials, are complex. The intricacy is not only from the
component materials but also from their interactions. The
natural variability of the structure and properties of wood
materials also complicate these interactions. The
densification resulting from compression greatly affects the
structure and properties of the wood-adhesive system which,
in turn, effects the progress of the other mechanisms (such
as vapor convection and associated heat transfer).

A number of research workers have studied the physical
and chemical phenomena of wood composites related to hot
pressing (including for example, Strickler, 1959; Suchsland,
1967; Humphrey and Bolton, 1979; Humphrey, 1982; Smith,
1982; Humphrey and Bolton, 1985; Zavala, 1985; Geimer et
al., 1985; Kamke and Casey, 1988b; Ren, 1988; Humphrey and
Bolton, 1989a, 1989b; Bolton and Humphrey, 1989a; Humphrey

and Ren, 1989; Hata, 1990a; Wolcott et al., 1989). Most have used empirical methods, which provide good experimental data to support general descriptions of the process. Few, however, attempted to address the problem numerically and thus provide the necessary fundamental understanding (Humphrey, 1982; Kayihan and Benjamin, 1983; Humphrey and Bolton, 1989a, 1989b; Wolcott et al., 1990). A limited number of researchers have worked theoretically, and some hypotheses have been developed (Chow, 1969; Collett, 1972). However, most of them did not include the rheological behavior of materials during hot pressing. None of these have apparently been supported or verified experimentally.

Experimental techniques, numerical methods and computing technologies have enabled viable models and techniques to be developed for studying the wood-adhesive system. Humphrey (1982) pointed out that computer simulation of physical phenomena during hot pressing process (incorporating heat and moisture transfer, adhesion and rheological behavior) may enable us to quantitatively predict the complete physical processes during hot pressing. However, before this may be achieved, each of the three areas (rheological behavior, heat and moisture transfer and adhesion aspects) must be quantified individually.

The rheological behavior of wood-adhesive systems during hot pressing, and the effects that temperature and moisture conditions have on these processes are the main

concern of this literature review and the research to follow. Interactions between thermo-hygro-rheological behavior and the other main physical processes will be only briefly discussed here.

2.2. Rheological behavior of wood composite materials

Wood-adhesive systems are rheological materials: the materials display elastic, viscous and plastic effects. Since wood composites products generally exhibit visco-elastic behavior in service, they are well known as visco-elastic materials, although they also display plastic and micro-fractural behaviors during manufacture.

The principles of rheology and its application to wood-adhesive systems will be discussed in the following sections.

2.2.1. Application of rheological principles

Rheology is a science developed from classical mechanics to study the time-dependent behavior of materials under load. According to the principle of rheology, the behavior of the materials may be represented by the superposition of the behaviors of elastic, plastic and viscous mechanisms (Eirich, 1958; Wang, 1984; Lodge et al., 1985; Bodig and Jayne, 1986; Findley, 1976). These basic

elements can be applied to represent the relationship

between stress and strain of the materials (Fig. 2.1).
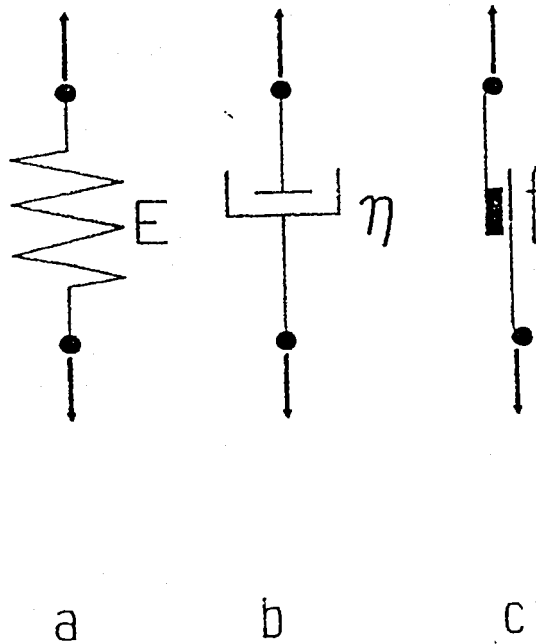
Figure 2.1. Rheological elements; a) elastic element,
b) viscous element, c) plastic element.

Elastic elements:

Elastic elements are represented by springs

(Fig.2.1.a). An immediate elastic strain response is

obtained upon loading. The response is time independent and

the energy absorbed by the materials upon deformation is

fully recoverable when the applied force is removed and the

system returns to its original dimensions (Zhao, 1982). The

chief characteristic of elastic strain therefore is complete reversibility.

Using common notation for the generalized Hooke's law for an isotropic materials subject to an uniaxial loading:

$$\varepsilon = \frac{\sigma}{E}$$
(2.1)

where, E: coefficient of elasticity.
       σ: stress.
       ϵ: strain.

Hooke's law represents material relationships where time dependency is excluded, whereas all processes occurring in response to an externally applied force are somewhat time dependent. Materials that obey Hooke's law (usually only at low strain levels) are said to be linearly elastic. However, it is entirely possible that a material may behave in a nonlinear elastic fashion (which may be represented by more than one linear spring combined together or by a single nonlinear spring).

Viscous elements:

Viscous elements are represented by dash-pots (Fig. 2.1.b). Materials that obey Newton's law are said to be ideally viscous (Newtonian). Viscous behavior is a time dependent response to external forces (Zhao, 1982).

Applying common notation of Newton's law:

$$\varepsilon = \frac{\sigma t}{K}$$

(2.2)

where, K: coefficient of viscosity.
       t: time.

The energy absorbed by the system is entirely
dissipated by non-mechanical (internal) processes and there
is no inherent tendency of the material to assume its
original dimensions. A relationship between strain and time
exists for any particular stress history.

Plastic elements:

Another ideally approximated by many materials in their
response to external forces is that of the St. Venant
material which is purely plastic (Lu, 1983). Plastic
elements are represented by friction blocks (Figure 2.1.c.)
where no strain occurs until the applied load exceeds the
yield stress of the material. When an externally applied
load reaches the yield stress, then high strain will
immediately occur.

$$\sigma = f$$

(2.3)

where, f: friction stress.

This deformation will remain when load is removed.
Plastic strain is defined as time independent although some

time dependent strain is often observed to accompany plastic strain.

Models for the rheological characteristics of a material may, therefore, be established by applying a number of the above basic elements in different arrangements.

A general model for visco-elastic materials:

Several models have been applied to composite materials. Burger's model, the most valid and applicable viscoelastic model, will be discussed here, since it has been used extensively.

Burger's model includes four elements to represent three different types of deformation: elastic, viscous and delayed elastic. Figure 2.2. shows the four-element model.

If the model is analyzed under constant uniaxial loading conditions, it may be simply described by the creep equation (Wang, 1984; Bodig and Jayne, 1986):

$$\varepsilon = \sigma * (\frac{1}{E1} + \frac{t}{K1} + \frac{1}{E2} (1 - e^{\frac{-E2*t}{K2}})) \qquad (2.4)$$

where, E1: property of elastic element 1.
      E2: property of elastic element 2.
      K1: property of viscous element 1.
      K2: property of viscous element 2.
      t: time.

Burger's model has been used to express a diverse range of types of visco-elastic material behavior (Findley, 1976). Its has also been applied to wood composites (for example, Bodig and Jayne, 1986; Smulski and Ifiu, 1987; Smulski, 1989; Tang and Simpson, 1990).
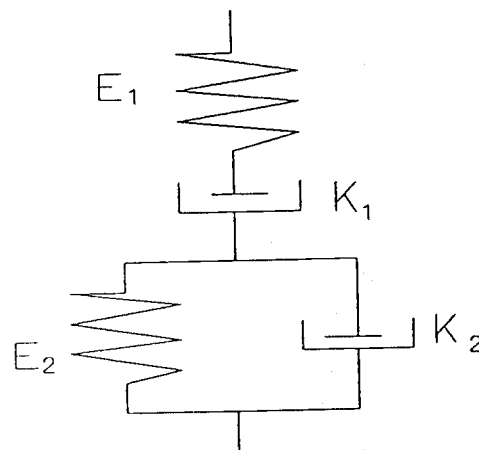
Figure 2.2. Burger's four-element model.

2.2.2. Rheological behavior of wood composites

Several studies involving the mechanical behavior of wood composite materials during manufacturing have been reported (Strickler, 1959; Suchsland, 1967; Bolton and Humphrey, 1989c; Smulski, 1989; Wolcott et al., 1990; Hata,

1990a). However, visco-elastic behavior has been given relatively little in-depth attention.

Since Kunesh (1961) first pointed out that hot pressed wood materials behave inelastically, several visco-elastic theories have been applied to wood composite manufacturing (Laufenburg, 1983; Kelley et al., 1987; Wolcott et al., 1990). However, most rheological models were developed for studying homogeneous solid materials under small deformation ranges or for studying materials in the liquid state. Their direct application to wood composites during hot pressing is limited by the fact that the relatively large deformation causes dramatic change in the structure and properties of wood-adhesive system.

Clearly, the rheological behavior of wood composites during hot pressing depends on the structure and behavior of the component materials (wood, adhesive and interface) and their interaction. External load and internal stress distribution and relocation; densification and partial fracture of the wood elements (while they are compressed, bent and twisted); intensive heat and moisture transfer; migration and penetration of adhesive as well as the development of adhesion; all these physical changes influence the rheological behavior of the system.

The rheological behavior of the materials therefore should be investigated not only as a system, but also in terms of the properties and behavior of the components.

2.2.2.1. Rheological behavior of wood materials

Cell wall compression theory has recently been studied by Kasal (1989). Wolcott and Kamke (1990) applied the theories of cellular materials and the visco-elasticity theory of amorphous polymers of Ferry (1980) in their study of compression of wood materials. These projects endeavored to directly apply and transform theories for other materials to wood composites. The structure of the wood composite and its effects on plastic deformation were not declared clearly. As stated earlier, however, it also involved (in addition to pure plastic deformation) micro-fracture and spatial rearrangement of wood elements. Since the above mechanical models oversimplified the causes of relative large deformation during hot pressing, their further refinement is limited.

2.2.2.2. Rheological behavior of adhesives

Rheological theory of adhesives must properly account for cohesion and adhesion (Marra, 1981; Ryutoku et al., 1990). A Torsional Braid Analysis (TBA) technique was developed by Steiner and Warren (1981, 1987) to study the rheology of adhesives as they cure. This was the first research which clearly attempted to study the rheological

properties of adhesives beyond the gelation stage which can be used in wood composites; even although these authors only considered changes in modulus of rigidity. However, the experimental conditions were obviously different from those that apply within composites during hot pressing. It did not include the effects of wood furnish materials and the variation of moisture content. Both of the above may significantly effect adhesion at the micro-structure level (Humphrey and Ren, 1989; Ren, 1988).

Humphrey and Ren (1989) appear to be first to directly study the isothermal adhesion kinetics of adhesive to wood bonds. Figure 2.3 shows an adhesion development curve for a powder phenolic to wood system. At the early stages of bond formation the adhesion strength appeared to depend on the instantaneous viscosity of the adhesive. As polymerization progressed, the adhesion appeared to increase.

The case of cohesion of adhesive of identical chemistry and molecular structure provides a basis for examining the rheological aspects of adhesive behavior (such as degree of polymerized and adsorption interdiffusion processes). The only important restraints that limit cohesion-type bonding concern the rheological character of the adhesive (Kaelble, 1971; Ren and Humphrey, 1990).
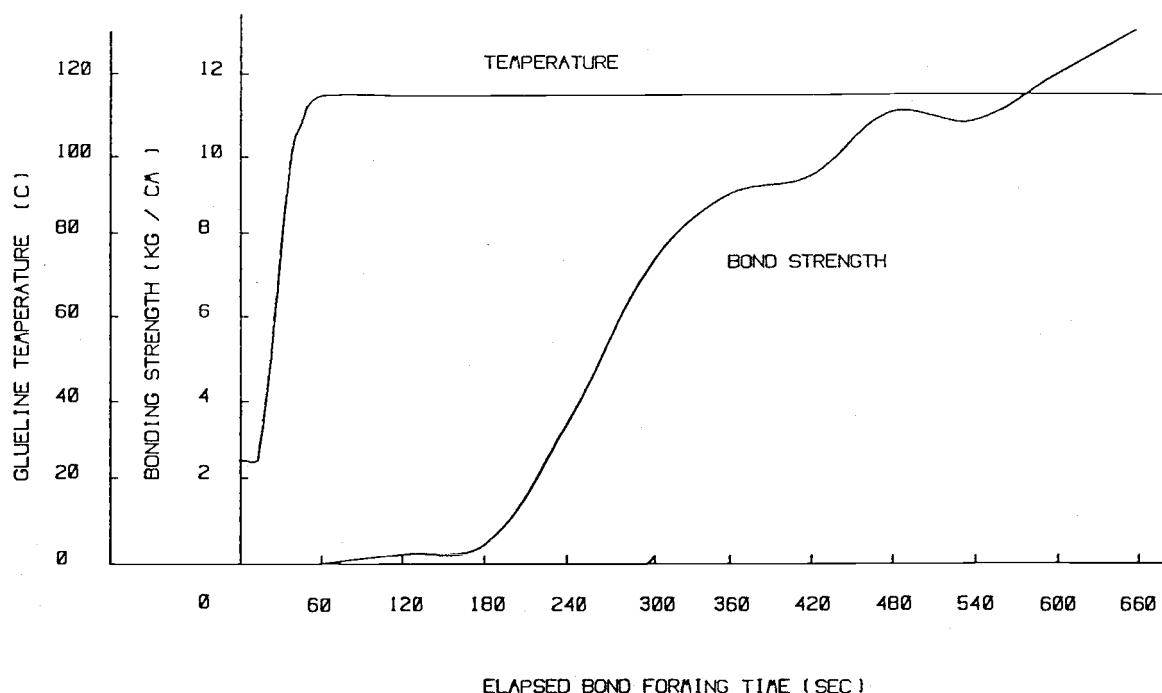
Figure 2.3. A typical curve of adhesion development
for powder PF to wood system (from
Humphrey and Ren, 1988).

Clearly, the area of wood-adhesive interactions and the
flow processes associated with bond development and the
ability to resist stress is highly complex. This is beyond
the scope of the present work but should, in this authors'
opinion, be the subject of much further study.

2.3. Effects of wood composite's structure on rheological
behavior

This section concerns the structures of wood-adhesive
systems and their effects on behavior during hot pressing.
Changes in structure (for instance, fiber orientation,

element structures or variation) of wood composites that occur during hot pressing have attracted little attention; most wood composites have been designed by trial-and-error methods without much prior knowledge of how their structure affects their behavior during processing. Once certain raw material structures had been found to yield products with moderately useful properties, they have been used with little further thought towards correction or improvement. This situation has changed somewhat recently with the application of scientific techniques. However, the progressive change in structure that occurs in composite materials during hot pressing is still not very refined.

Most reported methods for studying and analyzing the system during hot pressing processes were based on some idealized and simplified structure of the materials; where wood elements were allocated linear mechanical properties, uniform physical properties and stable geometric structures. These were placed in a non-continuous polymerized adhesive matrix, and adhesion between the wood and adhesive had been assumed to provide a joint which perfectly transferred stress (Strickler, 1959; Suchsland, 1967; Delollis, 1968; Humphrey, 1982; Zavala, 1985; Ren, 1988; Wolcott et al., 1990). For instance, many researchers preferred to simplify the structure to the wood and adhesive and assumed uniformly distributed porosity (Suchsland, 1967; Harless et al., 1987; Kelley et al., 1987; Wolcott et al., 1990).

The concept of simplified structure neglected that large deformations occurs along with a range of physical and chemical mechanisms. Although some ideal structural model may simplify the research work and create the opportunity to directly apply the theories from other areas, it obviously restricts further analysis.

A description of particleboard in terms of a statistical model of its structural variation was reported (Suchsland, 1967) (Fig.2.4).
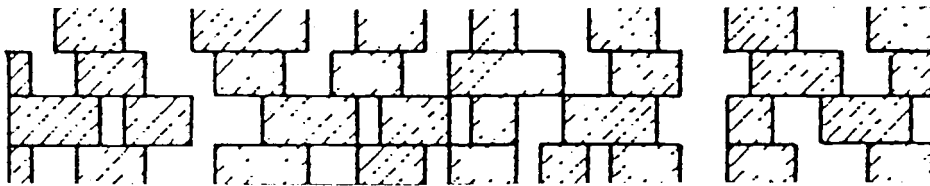
Figure. 2.4. Schematic illustration of particle mat
structure (from Suchsland, 1967).

The real structure (macro and micro) of wood-based composites are quite different from those over-simplified models (Mataki et al., 1972; Mark, 1972). Non-uniform spatial distribution of component materials is a general

characteristic of wood composite structures (Humphrey,

1982). For instance, wood composites are formed from wood

furnish materials (particles, veneers, and fibers) which

are only partially adhesive coated.

Sources of randomized structural variability include:

fracture, distortion and overlap of fibers or layers,

adhesive extraction or over-penetration, non-satisfied phase

contact, etc. (Collett, 1970; Humphrey, 1982; Geimer et al.,

1985; Bolton and Humphrey, 1988). Progressive changes in

structure may result from differential consolidation through

a composite's thickness. Such density profiles are due to

progressive migration of heat and moisture as the press

closes.

2.3.1. Effects of wood furnish material structures

Two main sources of random variability may be

identified in the composites; these are associated first

with the variability of the wood material, and secondly with

the geometry and orientation of the wood elements in the

consolidated composites. If wood-based composites are to be

considered engineering materials, then understanding of

their micro-structure will be necessary during both design

and manufacturing.

The effects of wood structure and properties on

composite structure and properties have been investigated by

too many workers to be cited individually; a selection includes (Kollman et al., 1975; Liang, 1981; Rosen, 1979; Strickler 1959; Siau, 1984; Skarr, 1972; Humphrey, 1982; Stewart, 1979; Stanish, 1986; Wengent and Mitchell, 1979; Marian, 1966; Chow, 1969; Clay and Kramer, 1988; Marra, 1981). The following research areas may be identified:

- wood structure and physical properties

- wood chemical properties

- wood surface energy and wettability

- wood properties affecting heat and mass transfer in the vicinity of the bond (permeability, hygroscopicity, conductivity, void volume etc.).

- orientation of wood elements in the composite.

- moisture content and temperature of wood.

Unfortunately, there appears to be very few reports concerning how wood composite structures change during the hot pressing process and how these effect the composite formation process and properties (Suchsland, 1967; Humphrey, 1982). Some of the above factors will be briefly considered in turn.

It is clear that wood structure and the orientation of components within both solid wood and composites has an effect on the performance of wood-adhesive systems. Upon compression of composite mats, densification will occur. Many anatomical characteristics of the interacting surfaces will then affect the nature of the compression and adhesion

process that may follow. These are likely to vary in response to general characteristics associated with species (cell wall structure) and such factors as the anatomical differences between earlywood and latewood (Clay and Kramer, 1988). For example, latewood generally has superior mechanical properties, but it is contended that the higher density (cell wall thickness) of this material results in more variation in swelling and shrinkage. This may lead to high stresses on the micro-structures both during hot pressing and in service.

The surface characteristics of wood furnish material directly influence the internal stress distribution. It also effects adhesive distribution and subsequent strength of adhesives bonds (Chow, 1969; Collett, 1972; Kelley, 1983; Wellons, 1980; Young, 1982). Earlywood exhibits good accessibility to adhesive mainly due to the larger voids of the fiber lumen. This generates a larger active surface area for adhesion but larger deformation (strain) is necessary to achieve a given density and interfacial contact.

In order to improve and design wood composite structures, quantitative description of structure and associated properties is more valuable than a statistical descriptive model. Some researchers have tried to link the mechanical behavior of composites to the characteristics of cellulose and lignin (Mark, 1972; Wolcott et al., 1990). The application of these theories during hot pressing has not

been completed, although such approaches may well have considerable merit.

2.3.2. Effects of the adhesive matrix structure

Marra (1981) likened the adhesive bond to a chain with nine links. Each of the nine links can be associated with specific types of behavior that affect both bonding and final product performance (see Figure 2.5.).

In Marra's model, links 8 and 9 represent the physical, chemical, and anatomical properties of wood; links 6 and 7 represent the nature of the subsurface of the zone, while links 4 and 5 represent the interfacial area where adhesion forces of wood and adhesive are supposed to engage one another. Links 2 and 3 are the adhesive layer that could be most strongly influenced by the chemical and physical properties of the wood. The center link reflects adhesive cohesion. Mechanical properties may, then, result from the behavior of any link in this hypothetical chain. This structural model demonstrates the wood-adhesive adhesion structure. However, it was not experimentally verified and does not provide any real data about how the structure progressively develops.
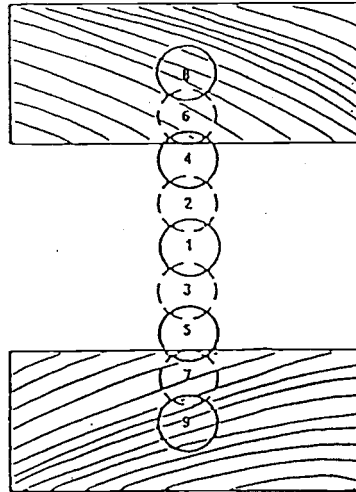
Link 1:   The adhesive film.
Links 2 and 3: Intra-adhesive boundary layer, strongly
                   influenced by the adherent.
Links 4 and 5: Adhesive-adherent interface, site of
                   adhesion forces.
links 6 and 7: Adherent subsurface, partially fractured
                   in preparing the surface.
links 8 and 9: Adherent proper.

Figure 2.5. Nine links of an adhesive bond (according
            to Marra,1981)

The molecular structure of most adhesives continuously

changes with time and temperature from a linear, or

partially cross-liked (pre-polymerized) form to a fully

cured three-dimensional structure. The adhesive's properties

therefore vary during hot pressing. Such variations lead to

the generation of three-dimensional networks throughout the

composite (Kelley, 1983; Nelson, 1974; Gent and Hamed, 1981;

Kyokong et al. 1986; Rice, 1981). However, the adhesive

structure is not a continuous (inter-connected) matrix

within wood composites since the quantity of adhesive is not normally sufficient to cover the total surface area of the wood furnish material. Furthermore, conventional formation techniques are not precisely controlled, and the interfacial structure of the wood composite is non-uniform (Humphrey, 1982; Ren and Humphrey, 1990).

2.3.3. Effects of interfacial structure

The interface is not only a geometrical boundary between the wood material and adhesive, but also between adjacent materials' elements. The interface is influenced by physical-chemical processes taking place during the interaction of wood and adhesive at the stage of composite formation (such as inter-diffusion of adhesive and other fluids, selective sorption, and catalytic effects). Furthermore, the effects of heat and moisture on the material influences stress levels at the interfaces; the later is due on part to dimensional changes of the cell wall that occur with moisture changes. (Castle and Watts, 1989; Ren and Humphrey, 1990).

The interfacial properties may effect hygro-thermo-mechanical compatibility of the components. The physical-chemical effects define phase contact completeness, and the nature, number and strength of physical and chemical bonds which are generated.

Reduction and elimination of the interfacial imperfections can be directly associated with the processes of internal stress relaxation (Kelley et al., 1987). Such effects may be of critical importance in the adhesion mechanisms in wood based composites and paper.

Techniques to fully analyze the structure of wood-adhesive interfaces are, unfortunately, still beyond our knowledge.

2.4. Effects of temperature and moisture

Heat and moisture affect the mechanical properties of the system, and this results in variations of structure during manufacturing, and in variations in service performance. Simultaneous heat and moisture transfer results in transient gradients of temperature, within-void vapor pressure, cell-wall moisture content, adhesive polymerization, and wood furnish material softness during hot pressing.

Springer (1988) suggested three steps for studying the hygro-thermo effects of materials. First, the distribution of temperature and moisture content inside the material are calculated. This work in the wood composite area has been tackled by Humphrey and his co-workers (Humphrey, 1982; Humphrey and Bolton, 1989a; Siau, 1984; Bowen, 1970; Hata, 1990). Second, from the known temperature and moisture

conditions, the hygro-thermal deformation and stress are calculated. Third, changes in properties and performance due to temperature and moisture are determined. Little research in the later two steps has been conducted on wood composites manufacturing.

A number of theories have been developed for a better understanding the mechanism of heat and moisture transfer both in solid wood and in wood-based composites. According to the reported research, temperature and moisture vary with time in a predicted manner (Humphrey, 1982). Heat is conducted into the system from platens that attain temperatures in the range of 70 to 230 °C. Both conductive and convective heat transfer occurs inside the system. Initially, moisture in the system (bound in the cell walls and associated with the adhesives) near the heated platens vaporizes, the partial pressure of water vapor increases in the outer portions of the porous system, and the vapor convects vertically to the center and horizontally to the edges of the composite. Examples of such investigations are quite numerous and included those reported by Humphrey (1982), Humphrey and Bolton (1989a), Skaar (1972, 1981), Siau (1979, 1980), Rosen (1979), Bowen (1970), Kamke and Casey (1988a).

However, the thermo-hygro effects on rheological behavior of the wood-adhesive system have not been quantitatively and directly studied until recently.

In the consideration of composite materials during hot
pressing, several parameters should be considered (Humphrey,
1982, Humphrey and Bolton 1985,1989a, Bolton and Humphrey,
1989c; Shout and Summerscales, 1981; Springer, 1988; Wolcott
et al., 1990) as following:

    a. temperature inside the material as functions of
       position and time.

    b. moisture concentration inside the material as
       functions of position and time.

    c. total amount of moisture inside the materials as
       functions of time.

    d. moisture and temperature effects on stress-strain
       distribution inside the material as functions of
       position and time.

    e. rheological behavior of the material as a function
       of time.

Variations of each of the above variables that occur
within the composite should be studied because they reflect
the thermo-hygro conditions under which the composite
structure is formed.

Since the theories governing the thermo-hygro effects
on composite materials has not been completely developed,
Tsai (1988) assumed that micromechanical theories remain
valid for the range of hygrothermal conditions that occur in
composites, that laminated plate theory and failure criteria
remain valid and only that the stiffness and strength

properties are effected. These assumptions may be used to simplify the modeling of temperature and moisture effects on engineering composite application. Since the mechanics which developed from general condition can be used for certain range of hygrothermal change, many theories from other research may also be applied to the thermo-hygro effects of composites. Micromechanics is used here because it can reduce the number of variables. However, Tsai's suggestion was developed for mainly with in-service behavior of composites in mind, rather than for the manufacturing process.

The provision of numerical models which account fundamentally for the contributory mechanism during hot pressing is very important. Several researchers have attempted to simulate the system using numerical methods of integration. Carruthers (1959) attempted to model temperature change or rate of heat penetration in particleboard. Bowen (1970) applied a two dimensional model to describe heat transfer in particleboard pressing, but he did not directly calculate convective heat transfer; this limited his model. Kayihan and Johnson (1983) developed a model which considered both heat and moisture flow theoretically. However, it was a one dimensional model and was short of rigorous physical analysis. Some relatively empirical research involving steam injection has also been reported recently (Hata, 1990).

Those works may be represented by one successful and realistic three-dimensional model which was established by Humphrey (1982) for heat and moisture transfer during hot pressing.

In this model, the physical dimensions of the composite while in the press are divided into small increments of length. Simulation progresses by considering interactions between these defined regions for small time increments. If the time increments are sufficiently small, steady-state conditions of temperature and moisture as well as vapor pressure may be approximated, and simple equations may be used to calculate flow of energy and vapor during each increment. Updating the status of all regions at the end of each time increment enables simulation to proceed. The updating procedure involves the calculation of new equilibrium conditions of temperature, adsorbed moisture content, vapor pressure and relative humidity for each region.

This model describes the heat and moisture transfer which takes place when a mattress of wood particles or fibers is hot pressed. It produces three dimensional distributions of temperature, absorbed moisture content, and within void vapor pressure and relative humidity.
The physics underlying the above mentioned researches on heat and moisture transfer will be briefly outlined in the following sections.

2.4.1. Temperature effects

Heat may be transferred in wood composite materials in three ways: conduction, convection and radiation (Humphrey, 1982; Humphrey and Bolton, 1989a, 1989b; Kamke and Casey, 1988a; Kollman et al., 1975). Heat conduction and convection are thought to play a major role in the hot pressing of wood composites; radiation is not thought to be significant.

During hot pressing, heat is transferred from the press platens to the center of the board until the temperature at the center of the board approaches that of the platens. On the other hand, when the temperature increases, differences between the board and outside temperature increase and some (usually relatively little) heat is transferred from the edge of the board to the atmosphere by Newtonian cooling. Far greater amounts of heat and water are lost through the edges due to the escape of water vapor. The unsteady-state heat transfer is therefore in three dimensions and is a function of time and the material's structure. A number of equations have been developed in this area. Most of them have limited applicability and are not conceptually difficult to derive (Welty et al., 1976; Zhang, 1983).

The rate of conductive heat transfer clearly depends on the magnitude of the temperature gradient and the thermal conductivity coefficient of the materials (Humphrey, 1982; Shao, 1989; Hata, 1990). Primary among the material

properties which effect conductivity are density, moisture content and the structure of the material (which effects the conductive pathways).

The combination of thermodynamic processes operative within wood-adhesive system during pressing are similar in their fundamental nature to those in solid wood during drying, but their variation is more complex since the structure continuously changes during pressing. The steepness of gradients and the resultant hostility of the environment within panels make rigorous understanding of the processes all the more important.

platten   core   plotten
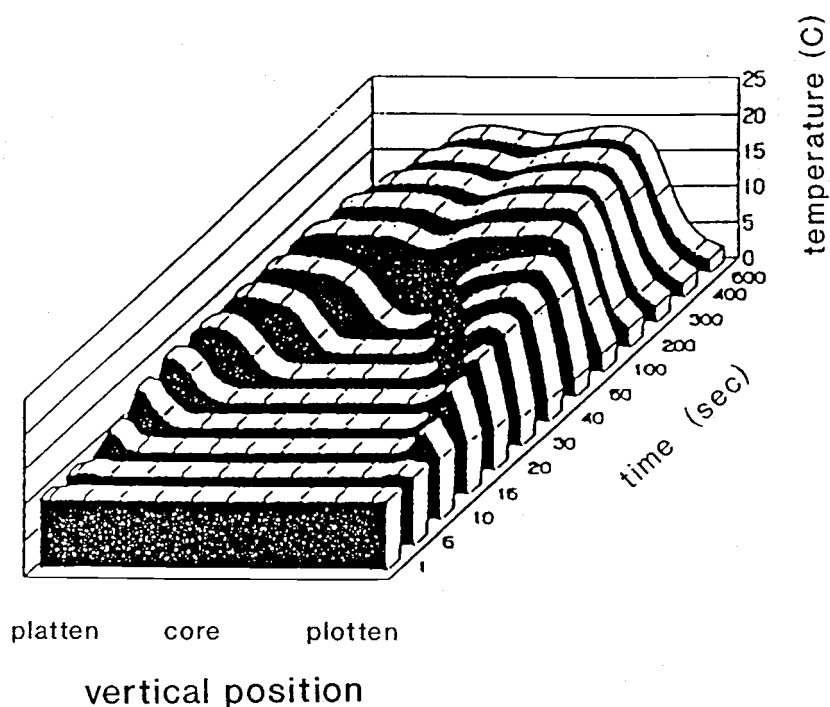
vertical position

Figure 2.6. Predicted temperature distribution
(from Humphrey, 1989).

Figure 2.6. shows a typical computer simulated temperature distribution within an industrial panel in three dimensions. With time increases, the vertical position temperature distribution continuously varies until equal to the platen temperature.

Heat may influence the mechanical behavior due to the glass transition temperature (Tg) of the component materials, effects of moisture condition, and adhesive polymerization. Wood composites contain polymeric component materials. The effect of heat on the mechanical behavior, therefore, may be described by the equilibrium principle of temperature and time. This approach was originally developed for chemical engineering and the polymer industry. Mathematical applications of this principle, such as the Williams-Landel-Ferry (WLF) equation, which is popular in the polymer composites areas may possibly be applied here (Ferry, 1980; Seferis and Nicolais, 1983; Wolcott et al., 1990, Nelson et al., 1974). Wolcott and Kamke (1990) appear to be first to apply the WLF equation in the wood composite area by trying to quantify the effects of temperature on the viscoelastic behavior of the materials.

Since the rate of temperature rise will determine the adhesive polymerization rate and softness of the structure, both the heat and the associated adhesion influence the rheological behavior of the system. The adhesive effects will be discussed later.

2.4.2. Moisture effects

During the early stages of research, a number of workers noted that overall furnish moisture content effects physical properties of composites (Smith, 1982; Suchsland, 1967; Bolton and Humphrey, 1989b; Liang, 1981; Jr. Nelson, 1986; Simpson, 1980; Siau, 1980; Skarr, 1981). Strickler (1959) pointed out that the distribution of moisture affects layer density, modulus of rupture and elasticity, internal bond strength, and dimensional stability of particleboard.

The internal stresses and associated local densification are clearly associated with movement of water within the materials during pressing (Suchsland, 1967; Zavalar, 1986). Some investigations (Humphrey and Ren, 1989, Ren, 1988) have suggested that tensile strength of wood composites is maximized when they are formed at steady-state of moisture contents between 8 to 10%.

It should also be remembered that localized moisture values vary greatly within such panels during pressing, so initial moisture values do not provide any fundamental information upon which the processes may be characterized (Humphrey, 1982).

In general terms, free water evaporates from liquid surfaces as energy is applied. As the moisture content of a system of wetted wood materials decreases below fiber

saturation point the attraction between the wood and the adsorbed water molecules increases (Siau, 1980; Skarr, 1972; Moore, 1983; Pimentel and Spratly, 1969), and so does the energy needed to remove them. In the pressing of most wood composites, phase change and subsequent convection of water vapor contributes more than conduction to the rapid transfer of heat energy into the board center. This has been asserted by a number of workers (Strikler, 1959; Siau, 1979) and confirmed by Humphrey (1982, 1989).

The rate at which moisture moves through the composite is clearly a function of energy input, the energy associated with the change of phase of adsorbed water into water vapor, and subsequent diffusion and re-adsorption of the vapor (Skarr, 1972; Humphrey, 1982). This diffusion of water vapor leads to the re-distribution of adsorbed water within the system and the development of gradients of moisture content in the three dimensions of the composite. Moisture will be lost from the edges of the composite where only the partial pressure of the water vapor in the surrounding atmosphere. Escape of vapor from the surfaces of the composite in the press will be prevented by the presence of the platens.

Moisture movement from one location to another therefore relies upon localized gradients of temperature and moisture content, together with the hygroscopicity and permeability of the materials.

A typical simulated moisture distribution within an industrial panel in three dimensions is shown as Figure.2.7. With the time increases, the vertical position moisture content also varies.
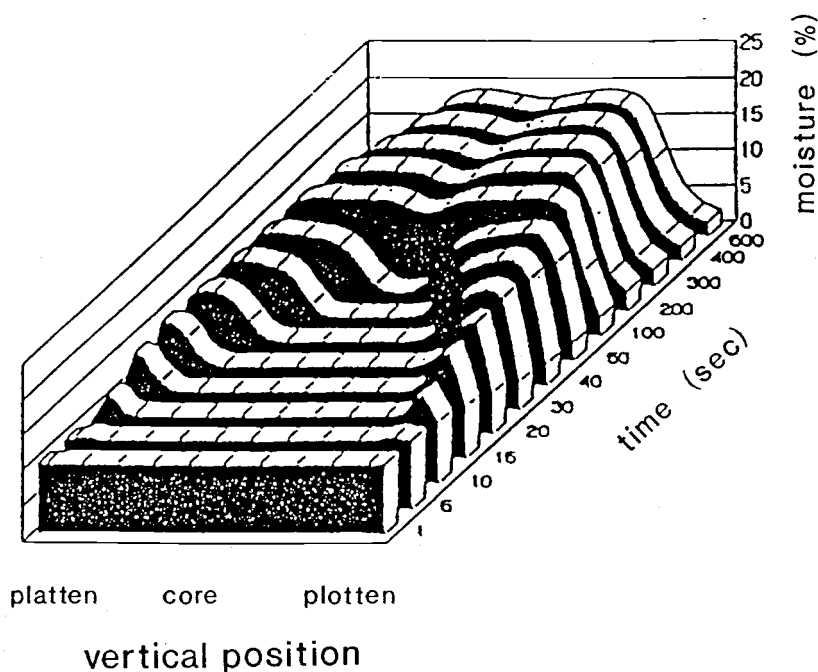
Figure.2.7. Progressive changes in predicted vertical
            moisture distribution during hot pressing
            (from Humphrey, 1989).

The effects of moisture on mechanical behavior during the hot pressing is an important factor. Unfortunately, no report about the moisture effects on the rheological behavior of wood-adhesive systems during hot pressing can be found.

2.4.3. Effects of temperature and moisture on the

rheological and bonding behavior of adhesives

A brief and preliminary review of the effects of
localized temperature and moisture conditions on the
behavior of adhesive is discussed in this section - although
it is not the main focus of the present work.

As would be expected for a thermosetting adhesive, the
influence of temperature on the development of bond strength
is significant, especially in the initial stages of the
bonding formation. The viscosity of many adhesives is
clearly effected by their temperature. The higher the
temperature the lower the viscosity. This is providing that
polymerization does not overcome this effect. Such changes
in the rheological properties of adhesives while within
composites during hot pressing are still not well understood
(Anderson et al., 1977; Humphrey and Bolton, 1979, 1985;
Steiner and Warren, 1981; Brady and Kamke, 1987; Steiner and
Warren, 1987; Humphrey and Ren, 1989; Ren and Humphrey,
1990). When all other factors (such as moisture content)
are held constant, bond strength development is a function
of temperature and forming time (Kaelble et al., 1971;
Anderson et al., 1977; Ren, 1988).

$$S = \quad f \quad (T,t) \tag{2.5}$$

Where: S = accumulated strength (Pa)
       T = forming temperature ($^{\circ}$C)
       t = forming time   (sec)

Indeed, for many adhesive systems investigated, it has been found that bond strength follows the Arrhenious relationship (when the log of isothermal strength development rate is proportional to absolute temperature (Humphrey and Ren, 1989).

With care, the principle of superposition (and numerical methods) may be used to predict the development of bond strength under different temperature conditions. This concept also can be used when attempting to model the unsteady-state temperature and moisture conditions that occur during pressing (as described in sections above).

The combined influences of both moisture content and temperature on the development of adhesion is also significant (Ren, 1988). Recent studies reported that the moisture content of 10% produced higher bonding rates in wood-adhesive adhesion than those at 4% and 16% in an actual controlled steady-state condition of moisture (Humphrey and Ren, 1989). Wellons (1982) pointed out that the moisture in wood determines glueline moisture content and thus effects both the depth of adhesive penetration and the curing time of aqueous adhesives. Figure 2.8. shows the development of adhesion under different moisture conditions (4, 10, and 16%) and temperatures of 115 °C and 110 °C. In this work, both temperatures and moisture content clearly affected the early stages of adhesion. This suggests there is a range of

moisture values which are optimum for the rapid initiation of adhesion.
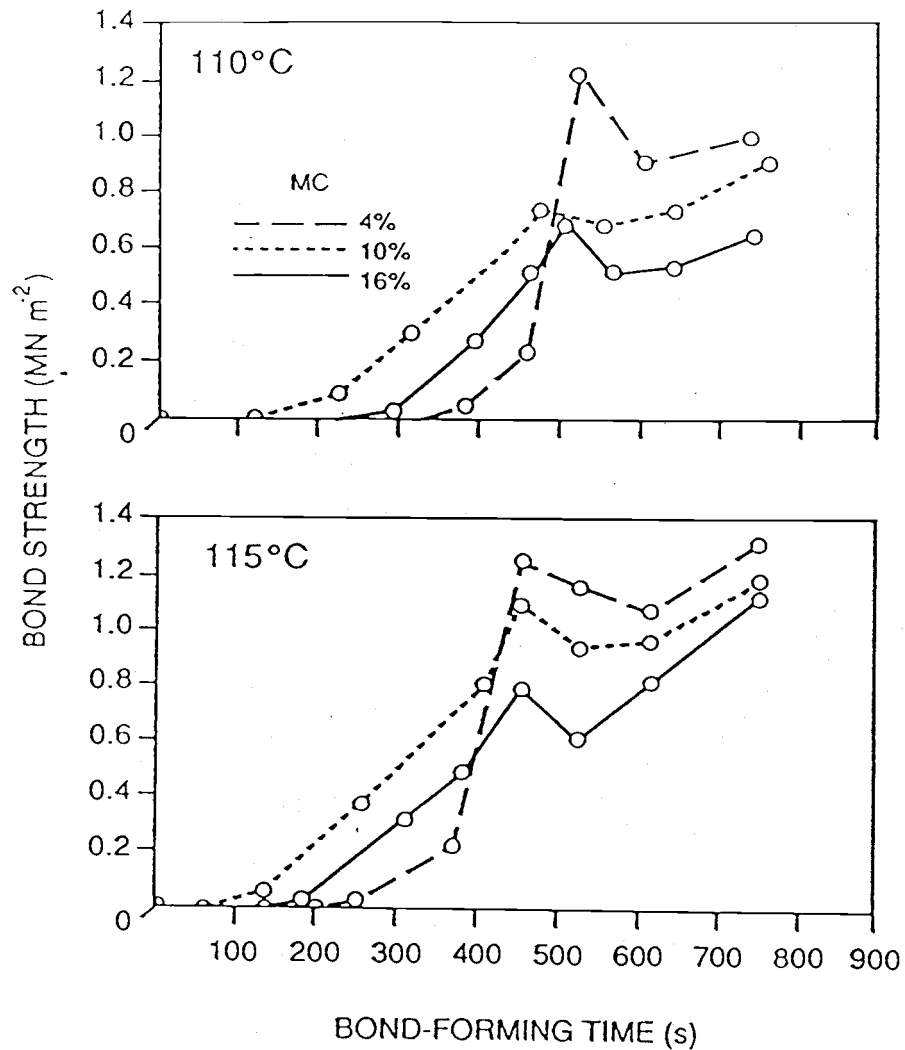
Figure 2.8. Development of wood-adhesive adhesion under different forming temperatures and moisture conditions (from Humphrey and Ren, 1989).

The effects of adhesive and adhesion on rheological behavior during pressing will be reviewed in the following section.

2.5. Effects of adhesive and adhesion on rheological
      behavior

Some rheological characteristics of adhesives and their
interaction with the conditions that occur during hot
pressing have been observed (Steiner and Warren, 1981; Ren
and Humphrey, 1990). However, because the contribution of
the rheological behavior of the adhesive to the behavior of
wood-adhesive system is complex, the behavior of adhesive
during hot pressing has not been understood clearly.

The rheological characteristics of adhesive
continuously change during hot pressing while the adhesive
polymerizes from linear molecules to a three dimensional
network. The behavior of adhesive and its effects on
rheological behavior of wood-adhesive system play varying
roles at different stages during the hot pressing process.
By dividing adhesion development that occur during hot
pressing into four stages, A, B, C and D as in Figure 2.9,
the rheological behavior of the adhesive and its effects on
the behavior of wood-adhesive system may be analyzed based
on the different stages.

Stage "A" may correspond to the adhesive melting,
squeezing and compressing, migrating and penetrating within
the system. Wood-adhesive adhesion is negligible and only
the result of viscous restraint. Since at this stage, true

adhesion does not take place, cohesive forces hold adjacent molecules of adhesive together.

Stage "B" may be the result of condensation reactions to form larger molecules and small networks. The viscosity of the adhesive is likely to increase rapidly but it still may be regarded as a fluid. The adhesive is soft and can become somewhat thermoplastic-like on heating. Its effects on the system therefore, is relatively small and may be omitted because of its low resistance to external load.
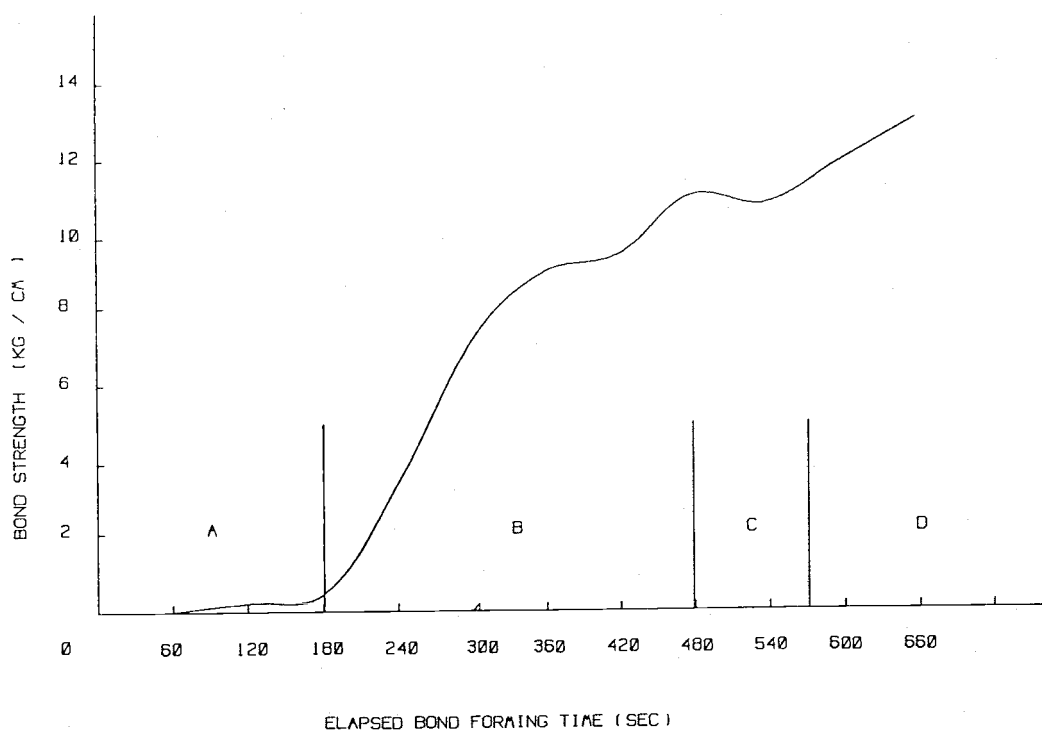
Figure 2.9. Four stages identified for the analysis of bond strength development (Ren, 1988).

The stage "C" corresponds to a slow development or reduction in adhesion. The cause of this discontinuity is not known. It may be that the adhesive begins to form a three-dimensional network where the initial or temporary molecular bonds are broken and rearranged. The viscosity of the adhesive may change relatively little during this stage.

Stage "D" of adhesion is well developed. The adhesive has reached a high level of chain-extension cross-linking reactions of the thermosetting adhesives results in a fully cured system. The deformation of the systems (both creep and relaxation), may be restricted by the fully cured non-continuous adhesive matrix. Since the adhesive matrix is non-uniformly distributed through the composite, localized micro-fracture may occur due to localized internal stress concentrations. The residual water vapor pressure inside the composite also may cause or increase this micro-fracture of wood-adhesive system upon press opening.

The whiskers of polymer (phenolic) drawn from the surfaces of adhesive-wood bond during the tension test at elevated temperature were observed (Ren and Humphrey, 1990). This suggests that the adhesive is deformable under such elevated temperatures and does display some thermo-plastic characteristics. There were short adhesive whiskers distributed non-continuously over the surface. Changes in viscosity of the adhesive would, most likely, affect the relative importance of adhesion deformation in the polymer.

According to the above discussions, the rheological behavior of wood composites during hot pressing clearly depends on the structure and behavior of the component elements (wood, adhesive and interface), environmental conditions, and their interaction.

CHAPTER 3.   RESEARCH STRATEGY

3.1. Introduction

The present research concentrates on an unified structure to study the rheological characteristics of the materials more than that of specific industrial products. In this way, the results may be generally useful for both scientific investigation and broad industrial application.

The study is focused on the combined rheological characteristics of wood, adhesive and interface during hot pressing. In future studies, the functions of the component materials within wood composites during this process and their relationship with other physical processes during pressing may be studied.

It is therefore an objective of the present work to develop the techniques and rheological models to numerically evaluate the rheological characteristics of furnish material behavior under the diverse conditions that occur during the hot pressing. Physical descriptions may be established based on the theoretical analysis and experimental results.

3.2. Structure of test materials

Since most deformation occurs within the wood fraction of the composite materials (not within the adhesive and

interfaces), the wood components dominate the rheological behavior of the whole system during hot pressing. Rheological behavior of the other components within the system are thought to be relatively insignificant compared with the behavior of wood furnish materials -- especially during the initial stages of hot pressing. At this stage, the contribution of the adhesive rheological behavior and polymerization is likely to be small.

Therefore, the rheological behavior of wood-adhesive system during hot pressing may be then approximately described by the behavior of wood furnish materials in a certain circumstances. The present research, consequently, is focused on the mechanism of wood furnish materials behavior during compression. The effects of the adhesive and interface on the rheological behavior of wood-adhesive system during hot pressing have been assumed to be relatively minor factors in initial stage of hot pressing process.

This research is conducted on samples which fall into the semi-macro structural (SMAS) level (dimensions lie between the micro-structure and industrial products). A study at the SMAS level may establish some connections between studies which based on micro-structure and macro-structure so that the research results may be useful for both industrial application and scientific analysis.

3.3. Rheological behavior at the SMAS level

When an external force is applied to a network of fibers or flakes, stress is transferred within the system through contact points of varying **effective interfacial area.** Stress is not therefore transferred through the network uniformly or continuously. Stresses which are transferred through this effective interfacial area may be called the **effective stresses.** The concept of the effective stress and effective interfacial area reflects the structure, property and mechanical response of wood composites based on their micro-structure. This concept may also be used to represent the material's "memory" of its history of behavior sustained during manufacture.

Under each applied force condition, the localized micro-structure of wood-based composites leads to a diversity of internal stresses. The variation of the effective interfacial area causes the variation of the effective stress:

$$\sigma_i = \frac{F}{S_i}$$

(3.1)

where: F: applied force, (N)
S: effective interfacial area, (M^2)
σ: effective stress, (Pa).
i: position within the board.

Consequently, if the localized strength of materials is less than the effective stress, high levels of localized deformation occur. Localized effective interfacial area is

partially or completely reconstructed. Especially at the initial stages of hot pressing, the effective interfacial area is relatively small and the localized concentrated effective stress may be enormously larger than the externally applied load. Plastic deformation may be partly caused by localized micro-structure fracture but large part due to material relocation.

With the densification, the effective interfacial area is rapidly increased and the effective stress is continuously redistributed. The effective stress may subsequently level off until it approaches the value of external stress. In other words, the effect of external load is shared by more and more of the components within the composite as the density increases. Localized micro-fracture and the quantity of micro-structural relocation are reduced. The component materials begin to act together as an united (composite) material which consists of the behavior of wood, adhesive and interface. The effects of this sequence on the rheological characteristics of wood-adhesive system are outlined in sections to follow.

Figure 3.1. represents the typical rheological behavior of a wood composite material under compression.

Rheological behavior may therefore, be classified into four different sources of strain (plastic and micro-fracture, elastic, viscous, and delayed elastic). A five-

element rheological model has been established to describe

these types of behavior (Figure 3.2).
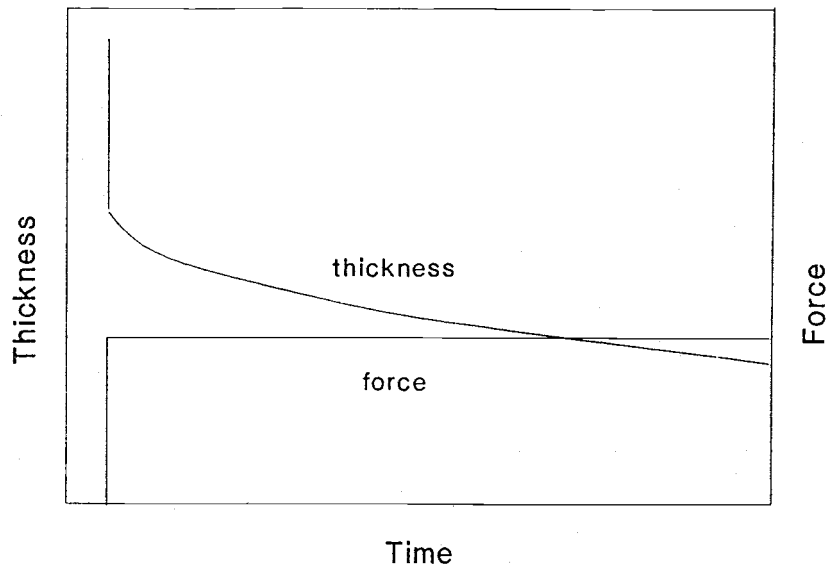
Figure 3.1. Typical rheological behavior of a wood
composite material under compression.
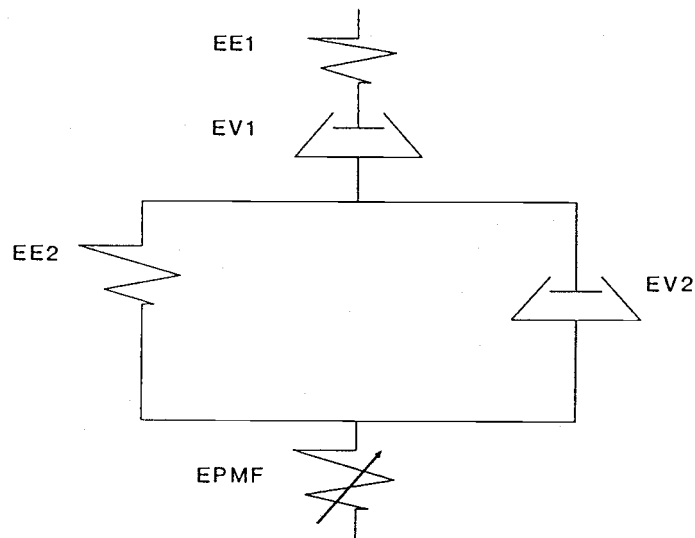
Figure 3.2. A five-element rheological model.

The role of each element is considered in turn. As pointed out in chapter 2, upon compression, the materials are instantaneously deformed due to elastic, plastic and micro-fracture behavior. The recoverable instantaneous deformation may be represented by an elastic (spring) element (EE1 in Fig. 3.2). The applied load is proportional (though nonlinearly) to the deformation, the response is time independent, and the energy absorbed by the material upon deformation is fully recovered when the external force is removed.

The non-recovable instantaneous deformation is caused by the Plastic and Micro-Fracture (PMF) effects which can be modeled by an Element of Plastic and Micro-structure Fracture (EPMF). No strain occurs until the effective stresses exceed the yield strength of the localized micro-structures. At that time, the micro-structure yields and some micro-fracture takes place, and a portion of the micro-structure is relocated. Since the yield strength depends upon the micro-structure of the material, it changes continuously while the structure changes. Such structural changes are non-recoverable. PMF behavior appears to play an important role in wood composites manufacture; especially in the initial stages of consolidation. It is here proposed to develop a new element to represent this behavior which includes the plastic relocation and partial fracture of the micro-structure.

After instantaneous modes of deformation, the material continues to deform, even under constant load. This deformation is attributable to non-recovable viscous behavior and delayed elastic behavior. The later is recoverable after sustained unloading.

Non-recovable viscous behavior can be modeled by a viscous element (EV1) which is represented by a dash-pot. The energy absorbed by the system is entirely dissipated and there is no inherent tendency to assume original dimensions. Delayed elastic deformation may be presented by elastic (EE2) and viscous elements (EV2) arranged in parallel.

Since each element represents part of the rheological behavior, the deformation of the material is a superposition of the five elements' behaviors. It is not conceptually difficult to mathematically describe the combined effects of these elements. This model may be represented by the following structural equation:

$$RB = EE1 + EPMF + EV1 + EE2/EV2 \qquad (3.2)$$

where, RB : represents the rheological behavior.
         +   : serial connection.
         /   : parallel connection.

A mathematical description of the five-element model could be represented by the following rheological equations:

$$\sigma + (\frac{\frac{K_1}{E_1 PMF}}{E_1 + PMF} + \frac{K_1 + K_2}{E_2}) \frac{d\sigma}{dt} + (\frac{K_1 K_2}{\frac{E_1 PMF}{E_1 + PMF} E_2}) \frac{d^2\sigma}{dt^2} = K_1 \frac{d\varepsilon}{dt} + \frac{K_1 K_2}{E_2} \frac{d^2\varepsilon}{dt^2} \qquad (3.3)$$

where, E1 : represents constant of EE1.   Pa.
        K1 : represents constant of EV1.   Pa * sec..
        PMF: represents constant of EPMF. Pa.
        E2 : represents constant of EE2.   Pa.
        K2 : represents constant of EV2.   Pa * sec..
        σ : stress.   Pa.
        ε : strain.   mm/mm.
        t : time.   sec.

At least some of the elements for present system behave in a nonlinear fashion. Since the materials sustain very large deformation (strain) during hot pressing, the variation of the structure significantly effects the behavior. It appears from preliminary analysis that reasonably reliable predictions of the materials' behavior may be made if the nonlinear nature of the system is linked to a structural property -- namely that of density. This assumption will be discussed in the next section and will be developed further in chapter 5.

Consequently, the definition of each element should be considered here as functions of structural properties, such as density. Any variation of the stress or density may vary the rheological characteristics of each element.

3.4. The link between system density and rheological
     characteristics

Density was applied here to establish the links between
the rheological behavior and structure. The use of density
is convenient since density changes continuously as pressing
proceeds and may be easily inferred. Localized density
variation, which represents how the micro-structure varies
under localized effective stress and the combined effects of
temperature and moisture condition, shows the nature of
rheological behavior of wood composite during hot pressing.
It is fully acknowledged that more refined analyses could be
developed which account for micro-structural changes which
may not directly be associated with density changes. Such
analyses are, however, likely to be very complex and have
yet to be developed.

The study of the rheological behavior in terms of
density is therefore an acceptable rigorous approach. It
also may offer easily measured and controlled parameters
which will be convenient for potential industrial
development work. The present approach really was, however,
likely to provide particular useful models in the short
term.

3.5. Temperature and moisture effects

Although, heat and moisture transfer have been studied before, relationships between temperature and moisture content and rheological behavior during hot pressing have not been quantitatively established. The effects of these variables on rheological behavior are an important part of this research.

Rheological behavior of wood composite furnish materials first was studied under steady-state conditions of temperature and moisture. Then, the effects of unsteady-state conditions of temperature and moisture, which occur during hot pressing, may be dealt with numerically in future work based on the results of the analysis from the steady-state conditions.

In the present research, experiments were performed on specially formed fibers disks while under a average of iso-thermo-hygro-conditions. Iso-thermo-hygro conditions were obtained by the specially designed experimental technique and equipments.

3.6. Research process

According to the previous analysis, this research work was conducted to understand the rheological behavior of wood furnish materials under the conditions that occur during the

hot pressing process. This research included: 1) applying rheological concepts to the hot pressing process, 2) establishing a rheological model of the materials, and 3) developing experimental techniques and equipment to provide experimental results. Rheological behavior as functions of structure (density), temperature and moisture condition have been investigated and predicted. Efforts to understand and numerically reproduce the thermo-hygro-rheological behavior of the tested materials have been contemplated.

The experiments were conducted under a range of test conditions of compression pressure, temperature and moisture content while all other conditions were held constant (the thermodynamic environments are maintained constant and uniform throughout each test). Under these conditions, varying stresses were applied and resultant deformation was recorded. The non linear characteristics of five model elements were determined from the experimental results. This procedure was repeated for a range of steady-state temperature and moisture conditions to enable a non-linear thermo-hygro-rheological model to be developed and experimentally verified.

CHAPTER 4. MATERIALS AND METHODS

4.1. Materials

Wood fibers were selected as the primary test material
in the investigation since they can be used to study the
properties of wood materials without (or at least with
reduced) influence of the natural variability of solid wood.
Furthermore, it is considered that the greatest potential
for new product development depends on the use of individual
fibers (rather than flakes, particles or veneers). Since
wood fibers can be formed in different methods and in
different dimensions, the natural defects of wood fiber may
be uniformly distributed throughout the test specimens and
the influence of defects may be minimized. Therefore, the
results of wood fiber study are more effective and accurate
than that of other type of wood materials to show us the
real nature of materials and as possible references for
further research work.

Wood fibers for this research were obtained from the
Evanite Hardboard Mill (Corvallis, Oregon). The raw material
for the fiber process came from several sources including
plywood mill residues (predominately, 90 - 95%), and wood
chips of whole trees (5 - 10%). Wood fiber used in the
present study consisted of about 95% Douglas-fir
(Pseudotsuga menziesii) and 5% Hemlock (Tsuga heterophylla).

Wood fibers were defiberated with a thermo-mechanical defiberator (TMP method) at the Evanite mill. Therefore, the properties of fiber were less influenced than that of other manufacturing methods, for example, the effects of chemical methods. The fibers, which were collected near to the port of the defiberator, did not include adhesive or wax. They were stored at about 75% MC in a cold room (8 to 10 °C) to avoid possible bio-degradation, prior to use.

In addition to fibers, flakes of poplar wood (Populus spp.) were selected as the second test material. The result of this research obviously may be related with flakeboard manufacture. Poplar wood flakes were selected since it was also used in a cooperative project with Michigan Technological University (investigating unconventional pressing cycles at high moisture content and low temperature).

Since this thesis is mainly concerned with physical principles and experimental techniques, the discussion about the behavior of flakes will not be included; they are only included to demonstrate the capability of the experimental techniques.

A wide range of materials may be investigated in the future with the developed techniques. For instance, wood veneer may be selected as test material to investigate the behavior of plywood and laminated veneer lumber (LVL). Furthermore, the rheological properties of combinations of

natural and synthetic fibers could be investigated. These may well be important constituents of composites of the future.

4.1.1. Specimen preparation

Preparation of wood fiber specimens

A metered quantity of fiber was blended with an excess (95%) of water in a laboratory blender until the fibers were well separated. The blending time was short (30 sec) so that the fiber structure and properties were not mechanically disturbed.

The fiber slurry was then transferred to a hand sheet forming system. The water was vacuumed from the fiber slurry through a fine screen, and a relatively uniform fiber network was formed.

The wet fiber disks were conditioned in a range of environments to achieve target equilibrium moisture contents.

With this system, the dimensions of wood fiber disks may be varied in response to the maximum required consolidation pressure available. In the present work, the disks were 90 mm in diameter, 25 mm in thickness and weighed 14 grams in the ovendry condition. The specimens could be

compressed at a pressure of 8 MPa on the available servo-hydraulic machine (capacity of 50 KN).

Circular specimens were adopted here because they do not contain any square corners which may perturb uniform boundary conditions.

Preparation of wood flake specimens

Flakes' average dimensions were 50 mm length, 10 mm width and 0.5 - 0.8 mm thickness. These were formed into disks carefully by hand to reduce possible variation. The flake disks were similarly pre-treated in conditioning rooms to reach the required equilibrium moisture content values. The flake disks were 90 mm in diameter, 20 mm in thickness and weight of 14 grams in the ovendry condition.

New specimens were used for each test to produce comparable results.

4.2. Experimental design

The experimental methods described here were designed to provide an experimental and quantitative understanding of rheological behavior and how both the temperature and moisture condition affect the behavior. Therefore, applied load, deformation, density variation, temperature and moisture contents were the main parameters considered in

this experimental design. Experimental design will be deliberated as following:

1. How to design experimental processes and select experimental parameters.

2. How to precisely perform the compression test, efficiently study the deformation process and the effects of temperature and moisture content.

4.2.1 The experimental approach

During the experiments, the environment was maintained constant and uniform throughout each test by pre-treating the specimen <u>inside</u> the test system until the desired conditions of temperature and moisture were attained throughout. Desired test conditions then, were maintained constant during each test by controlling the atmosphere inside the sealed testing system at the appropriate temperature and water vapor pressure.

Each specimen was tested under accurately controlled compressing pressures and steady-state condition of temperature and moisture. The stress and strain were measured and recorded for analysis. Following the experimental test, the specimens' dimensions and weight were recorded to double check whether the moisture content of specimen were accurately controlled during each test.

Experiments have been conducted under ranges of mean compression pressures (P). The rheological constants of the specimens may therefore be determined from the experimental results. The basic principle of the test is shown as Figure 4.1.
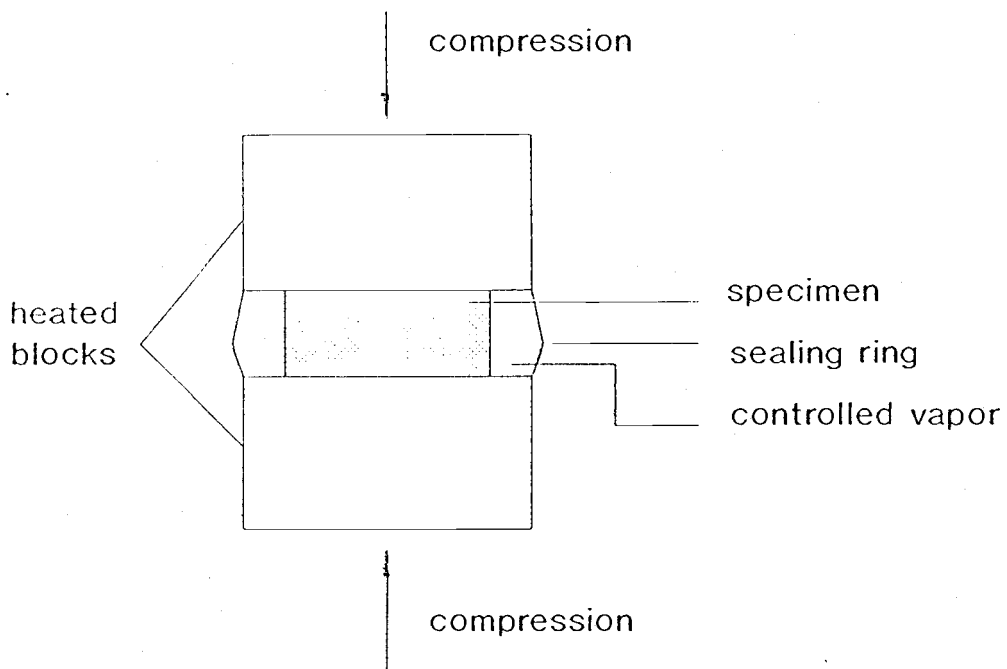
Figure 4.1. The basic principle of the test method.

Firstly, the temperature was held constant and the loads and deformations were measured for a range of moisture contents. Then, the moisture content of specimens was held constant and the loads and deformations were measured at a

range of temperatures. The combined effects of temperatures and moisture conditions were investigated in this way.

4.2.2. Compression and deformation

4.2.2.1. Compression

Compression pressures were pre-selected in the light of two main factors. First, since the results of our research may be used to improve existing products and also to design new composite materials, maximum pressures (the highest values used) should be comparable to peak loads applied in industry. More importantly, pressures should be selected based on scientific research requirements for understanding the fundamental mechanisms of wood composite materials.

The compressing pressures (platen pressures) conventionally used for wood composites vary both within and among each pressing cycle. Peak pressures typically range from 1 to 8 MPa. Pressures (P) were selected in the present work ranged between 1 and 6 MPa. Such a range enables material constants (such as elasticity, viscosity and plasticity), to be evaluated effectively.

A typical compressing pressure versus time curve applied to the specimens in this research is shown in Figure 4.2. From this curve, we can observe the compressing

pressure curve was designed with 22 steps for obtaining a diverse range of information about the material.

This curve may be sub-divided into three sections. Section I is the most important part and enables most rheological properties of the material to be obtained. Section II was included to enable the changes in rheological characteristics of the material to be quantified over an extended period. Section III was included to enable the relaxation of materials to be analyzed after maximum stresses have passed. The "spring-back" phenomena during hot pressing may relate to this section of the test cycle.
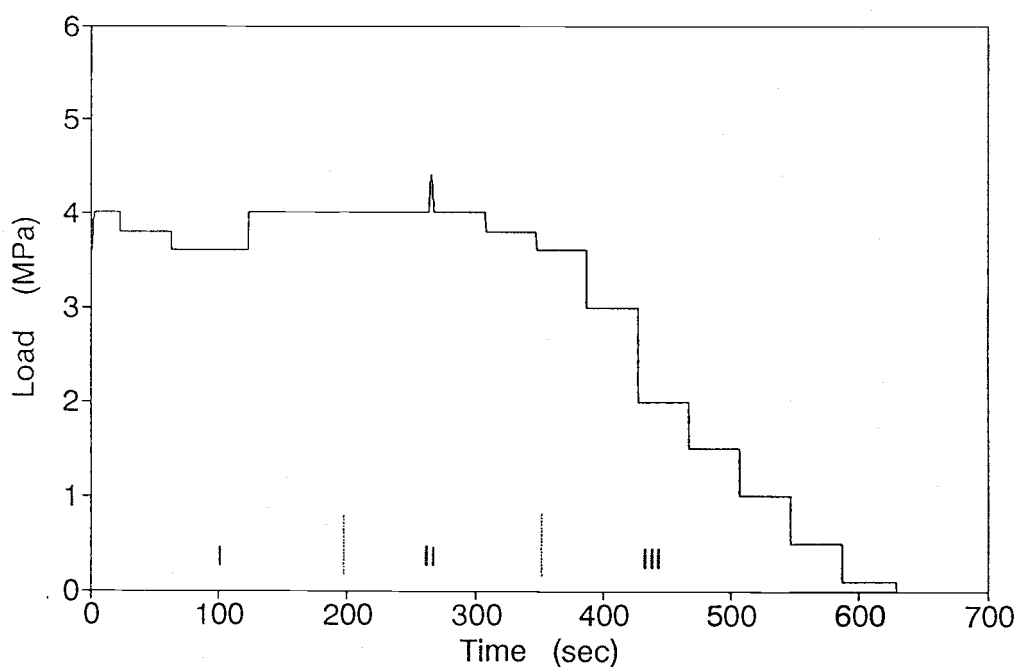
Figure 4.2. A typical pressure vs time curve
(P = 4 MPa).

In the present research, the main emphasis was placed on the application of rheological concepts to the material, the establishment and verification of models, and the development of experimental techniques to support them. Indeed, the latter is the primary focus of the present work; model development is only of a preliminary nature to demonstrate the approach. Therefore, only the first section of the experimental test results will be applied in the analysis in this thesis.

Since the compressing pressures have to be varied within very small ranges during each test (to meet the requirements of the analytical techniques), pressure reductions during each test were limited to 5% of the average pressure (P). The maximum compressing pressure was 10% larger than the average pressure (P) to produce some extra required elastic-plastic deformation. The elastic-plastic properties of the material may then be derived from the resultant deformations. Since the density of the material clearly varied during each test, several average compression pressures (1, 2, 4, 6 Mpa) were used to establish a relationship between the rheological behavior and the structure (in terms of density). The range of pressing cycles employed are shown as Table 4.1.

Actual compressing pressures applied to the specimens inevitably deviated somewhat from the above control (or target) values. This was due to the limited sensitivity of

test machine controlling system. However, this kind of

variation was very small (within ± 0.1% of the target

values).

Table 4.1. The range of compressing pressures used in
the experiments.

Section	Step No.	Duration (sec.)	Compression Pressure (Mpa)			
	1	0.4	0.0	0.0	0.0	0.0
--	2	0.6	0.9	1.8	3.6	5.4
	3	2.0	1.0	2.0	4.0	6.0
I	4	20	1.0	2.0	4.0	6.0
	5	40	0.95	1.9	3.8	5.7
	6	60	0.90	1.8	3.6	5.4
--	7	140	1.0	2.0	4.0	6.0
	8	2.0	1.1	2.2	4.4	6.6
	9	0.2	1.1	2.2	4.4	6.6
	10	2.0	1.0	2.0	0.0	6.0
II	11	40	1.0	2.0	4.0	6.0
	12	40	0.95	1.9	3.8	5.7
	13	40	0.90	1.8	3.6	5.4
	14	40	1.0	2.0	4.0	6.0
--	15	40	1.0	2.0	4.0	6.0
	16	40	0.5	1.5	1.5	1.5
	17	40	0.5	1.0	1.0	1.0
III	18	40	0.5	0.5	0.5	0.5
	19	2.0	0.1	0.1	0.1	0.1
	20	40	0.1	0.1	0.1	0.1
--	21	1.4	-0.8	-0.8	-0.8	-0.8
	22	0.4	0.0	0.0	0.0	0.0

4.2.2.2. Deformation

The deformation of specimens during each compression

test cycle was measured and recorded (deformation could also

be controlled with the system, but such position control was

not used in the main part of this investigation). A typical

curve of deformation versus time derived from the

compression curve of Figure 4.1. is shown in Figure 4.3.
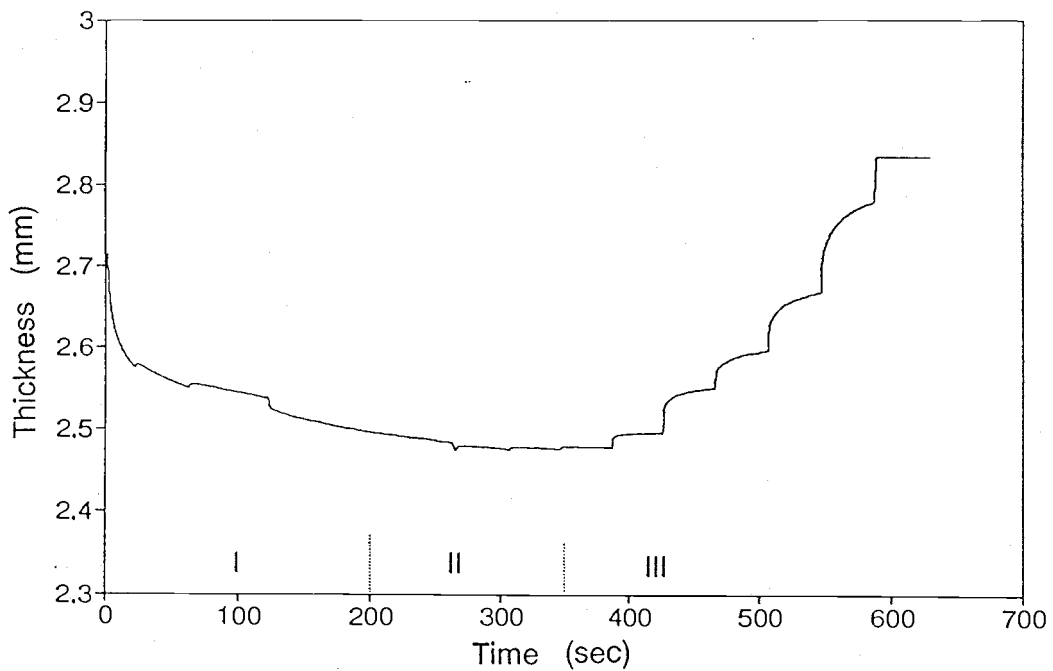
Figure 4.3. Typical deformation vs time curve for the
loading curve shown as Fig. 4.2.
(MC = 4%, T = 120 °C, P = 4 MPa)

Figure 4.4. shows more detail of load and resultant

deformation sustained during the first section of the test

curve (period I). The details of how the five constants for

the material may be derived from this curve will be

discussed in chapter 5.
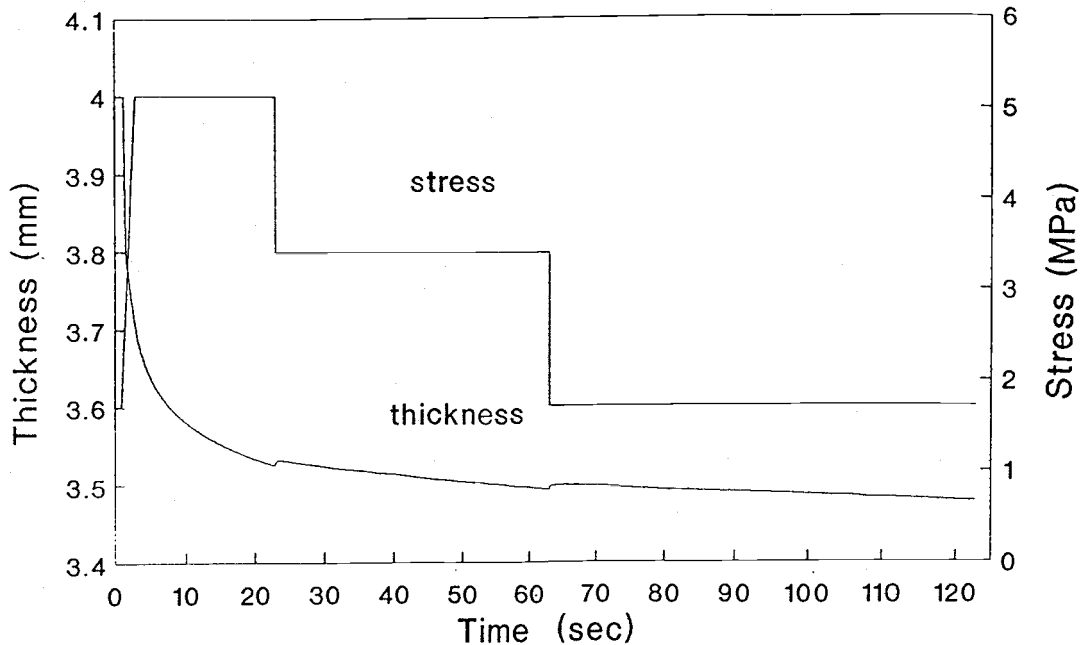
Figure 4.4. A typical curves of stress and deformation
vs time in the first section (I) of the
load control curve.

4.2.3. Investigating the combined effects of temperature

and moisture

Effects of temperature

The temperature of wood composite materials varies from

room temperature to about 200 °C during industrial hot

pressing. Considering the thermo-degrading susceptibility of

wood materials, a temperature range of 25 to 150 °C was selected for the present research. Temperatures of 25, 100, 120 and 150 °C were employed in the investigation. A broader range and more intermediate values may be explored in future research.

To achieve a constant and uniform temperature condition prior to each test, pre-treating processes within the test system itself were necessary. Figure 4.5. shows a typical temperature curve during a complete pre-treating and compressing cycle.
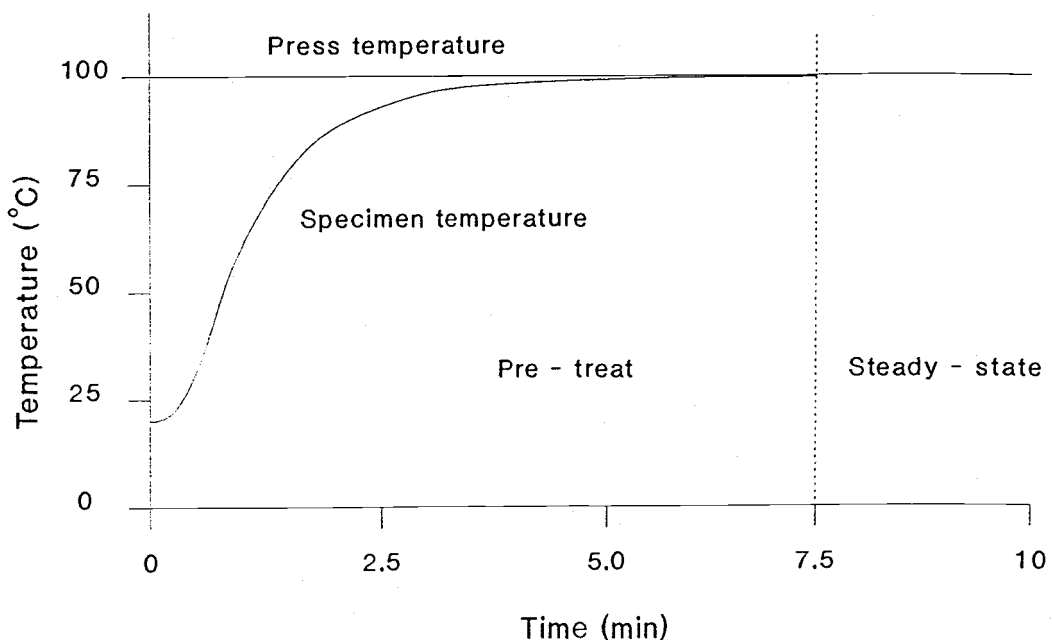
Figure 4.5. A typical temperature vs time curve during pre-treat and test processes (MC = 10%, target T = 100 °C, density = 250 kg/M^3).

From Fig. 4.5, we can see that the temperature of the specimen was raised from room temperature to the desired value. The temperature was then maintained constant during the compression test. The time needed to achieve a desired temperature varies with test temperatures, moisture content, density and fiber mass (specimen thickness for a given density).

Effects of moisture

The most difficult parameter to control and measure during each test was moisture content. In the present research, the temperature and pressure of water vapor were selected as the two variables to control the moisture contents of the hygroscopic specimens. We know that the equilibrium moisture content (EMC) of natural fibers is a function of the relative humidity (RH) and temperature of the environment, and the RH is also a function of vapor pressure and temperature. Therefore, if we can control temperature and vapor pressure, then we can effectively control the EMC.

An important consideration in measuring the partial pressure of water vapor in an atmosphere surrounding and penetrating the specimens was how to distinguish it from air pressure. Air was trapped inside the testing system and its pressure varied when the treatment vessel volume was varied

and when the temperature changed. In order to overcome this problem, the system was evacuated (air removed) prior to testing. In this way, subsequently measured pressures were entirely due to the vapor; the air pressure effects were thereby all but eliminated.

A vacuum pumping system was applied to produce sufficient evacuation at the beginning of each pre-treatment process. There was little residual air, and its effects on controlled pressures were calculated and compensated. In this way, we may assume that measured and compensated internal pressures were due to water vapor derived from moisture in the specimens or that added prior to system closure. Providing sufficient supplemental liquid water was added prior to the system being sealed, then the water that was inevitably lost during evacuation may not dry out the sample. After sealing and heating, sufficient water remained to enable the necessary vapor pressure accumulation to affect the necessary EMC when equilibrium was eventually reached.

Several assumptions are necessary in this approach.

a. Simpson's equation (1973) has been used here to relate EMC, relative humidity and temperature for wood fibers. The inaccuracy of this equation was assumed small enough to be accepted. In future studies, it may be necessary to characterize the hygroscopicity of particular fiber type.

From Simpson's equation:

$$MC = (\frac{K1 * K2 * h}{1 + K1 * K2 * h} + \frac{K2 * h}{1 - K2 * h}) * \frac{1800}{W}$$ (4.1)

where: K1 = 3.73 + 0.003642T - 0.0001547T2
        K2 = 0.647 + 0.001053T - 0.000001714T2
        W = 216.9 + 0.01961T - 0.00572T2
        h = P_{vapor} / $P_{saturate}$
        MC = moisture content.
        T = temperature

b. The final weight of tested (compressed) specimens can be used to indicate the final MC of the specimens after testing. This provided a means of evaluating the quality of control achieved during each test.

A range of moisture contents between 0 and 16% was selected (0, 4, 10, 16%). Figure 4.6. shows a typical vapor pressure curve measured during a pre-treating and compressing sequence.

In order to realize the experimental design, a new test system has been specially designed. This apparatus effectively consists of a miniature circular hot press with the provision for accurate load and temperature control. In addition, an attached environmental control system has been designed and used in this research. Peripheral sealing of the platens enables the atmospheres of controlled RH and temperature to be maintained around the specimen. A digital computer control system has been developed which enhances the servo-hydraulic test machine (MTS) performance thus enabling both compressive pressure and thickness of

specimens to be controlled dynamically. A digital data
acquisition system was also used to collect the test data.
More details about equipment design is presented in the next
section.
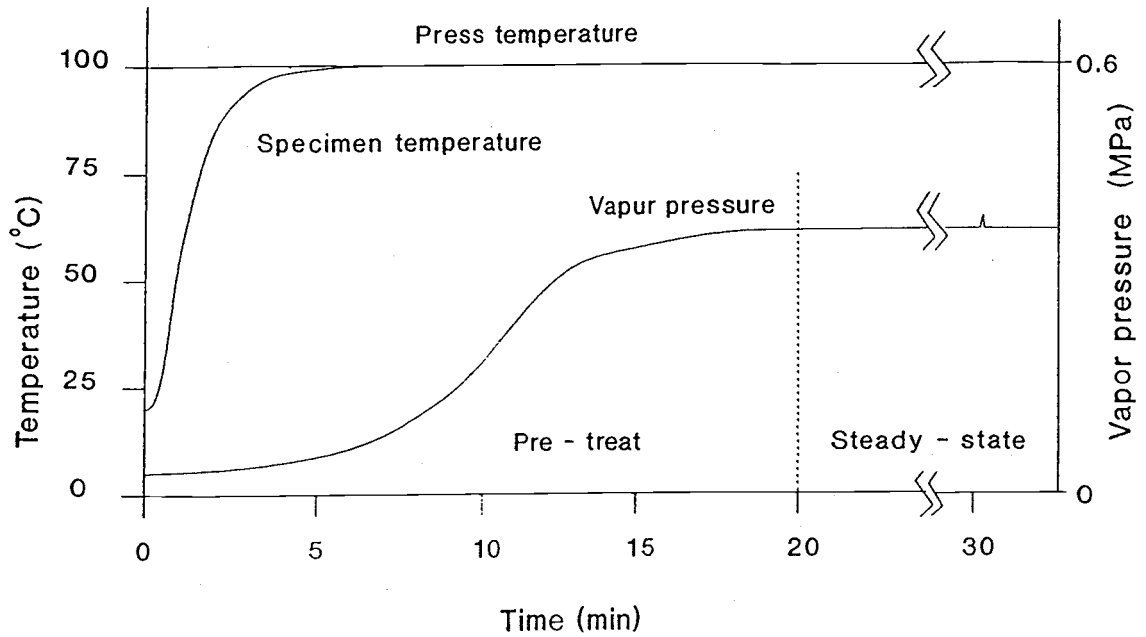
Figure 4.6. A typical curve of vapor pressure vs time.
(T = 100 °C, MC = 4%, Pv = .038 MPa)

4.3. Equipment design

According to the previous discussion, the test
equipment should perform the following functions:

1. Compress specimens with precise controllability and accurate measurement of load and deformation.

2. Maintain isothermal conditions in three dimensions throughout the specimens during each test.

3. Maintain iso-hygro conditions in three dimensions throughout the specimens during each test.

4. Provide capability of computer controlling the testing and data acquisition processes.

5. Experimental capability to conduct future research under unsteady-state conditions.

It was impossible to adapt any existing equipment to conduct this work. Therefore, new experimental arrangement was developed. This system and its development was the primary objective of the present research project. Figure 4.7. shows the miniature device which was developed for this research.

For the experimental miniature hot pressing system to have good heat transfer properties, the heat energy storage capacity (thermal mass) must be large enough to avoid large temperature variations during heat transfer from the platens to the test specimens. Insulation was designed to control internal distribution of temperature.
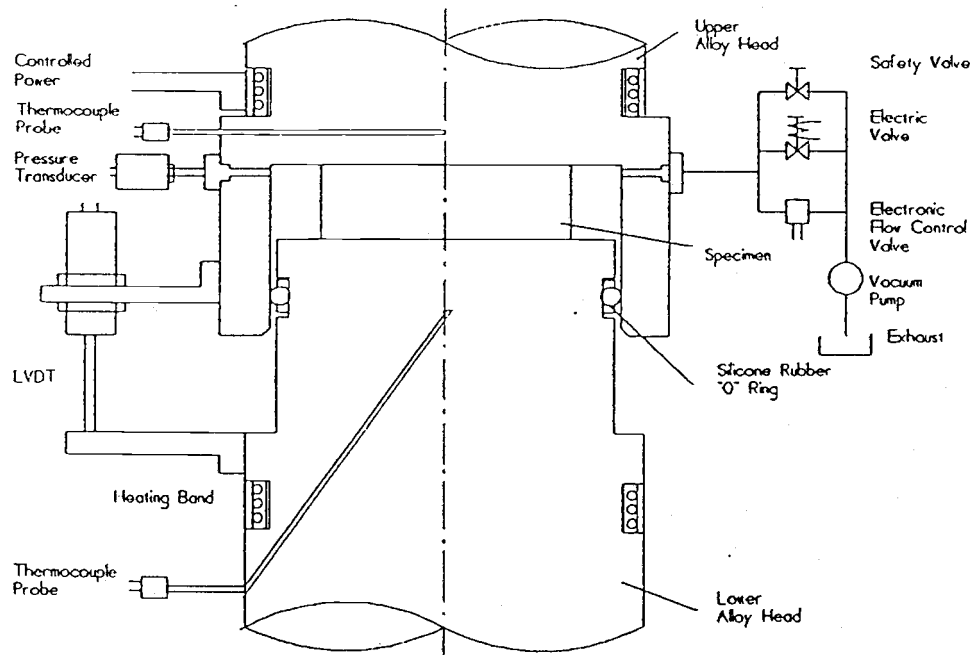
Figure. 4.7. A miniature thermal pressing system.

4.3.1. Affecting loading and measuring deformation

Two parts of the miniature hot press were assembled on the machine. One was attached to the top frame and the other was on the piston of the machine. The piston was able to be driven up or down by hydraulic power from a fast response power unit and control valve. A load cell of 50-KN capacity and LVDT of 150 mm range were applied to obtain a large test range. An extra LVDT of 50 mm range was directly assembled beside (60 mm away from) the hot press for precise measurement. Linking the LVDT directly on the pressing heads

improved the accuracy of measurements by avoiding vibration and the effects of thermally induced distortion of the MTS frame.

4.3.1.1. Compression measurement and control

In the load control situation (Fig. 4.8), desired compression pressure for each test was first generated by a computer program (see appendix I: a program for generating control loading pressure data). An operating program (see appendix I: a program for test operation) then converted the digital data to analog form by means of a digital to analog converter; this signal was transmitted to the MTS microprocessor.
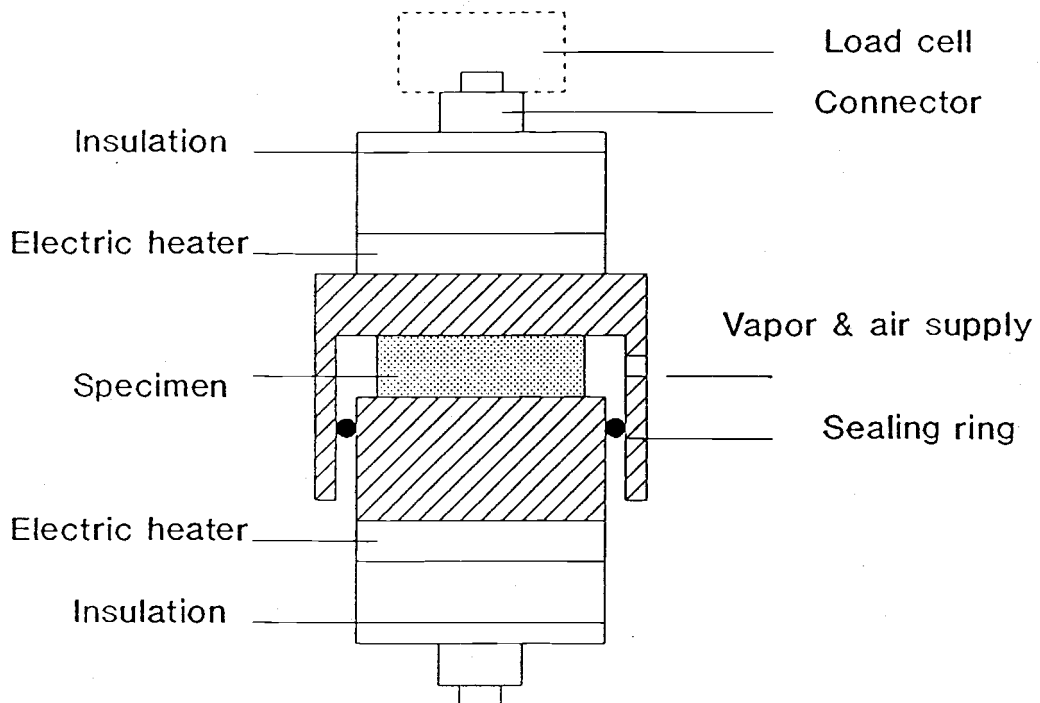
Figure. 4.8. The compression control and measurement scheme.

In the control loop, the desired control data (target value) was repeatedly compared with the measured value from load cell, and control system decided whether the load should be increased or not. If the actual load sensed by the load cell was less than the control value, the hydraulic system drove the piston up. The press was closed and pressure increased until the actual pressure approached the target value. The MTS machine then maintained the system constant (final position) until the next control cycle began. The signal analysis and control cycle were repeated every 0.2 seconds.

4.3.1.2. Deformation measurement and control

During compression, the relative movement between the top and bottom parts of the press was measured by the LVDT and collected by the computer with the data acquisition system so that the relationship of the compressing pressure and the deformation of materials can be established. A rigid material with high temperature resistance was used to connect the 50 mm LVDT to the miniature hot press. This minimized temperature influences.

The control system was also designed to be operated under position control so that deformation of materials could be controlled and resultant variations in stresses be measured. However, throughout the present research, load

control was used to establish the stress-strain
relationships.
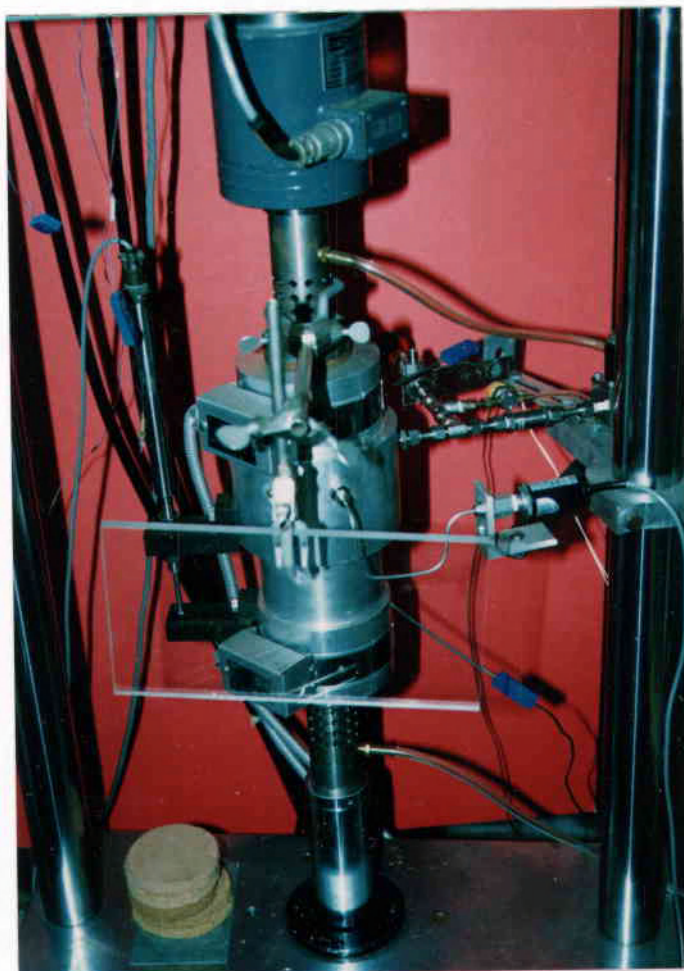
Figure 4.9. LVDT assembly photograph (LVDT vertically
assembled besides the press).

Since the two main variables, load and deformation,
were measured by the load cell and LVDT, and recorded by the
computer, which revealed a noisy signal related to some
equipment system components, no-matter how careful we were,
there were still some experimental errors. Much of the noise

was dealt with by passing the signal through a filter prier
to digitization. But some random errors remained.

However, the nonlinear regression of the large quantity
of experimental data at high correlation coefficient may
minimized these errors' influences (see chapter 5).

4.3.2. Temperature measurement and control

The desired temperature conditions encompassed a large
range for the different tests though they were constant
during each test. Two temperature variables (test system
temperature and specimen temperature) should be considered
here. Each of them will be addressed individually. The
following functions are necessary for this part of the
equipment design:

1. the tests must be conducted at temperatures varying
   between 20 to 150 °C.

2. the target temperature must be controlled within
   quite fine limits (± 0.5 °C).

3. heat transfer rates within the equipment and into
   the specimens should be maximized.

4. the sources of heat energy should be large enough
   and well enough controlled to minimize variation of
   temperature.

4.3.2.1. Test system temperature measurement and control

Thermocouples were used to measure sample and equipment temperatures. Two electrical band-heaters, two EUROTHERM analog temperature controllers (model 917) and two thermocouple probes (which were mounted inside the pressing heads) were used to measure and control the two parts of test system separately. Figure 4.10. represents the arrangement of band-heater and thermocouple probe on lower part of test system.

Heater   Thermo-probe
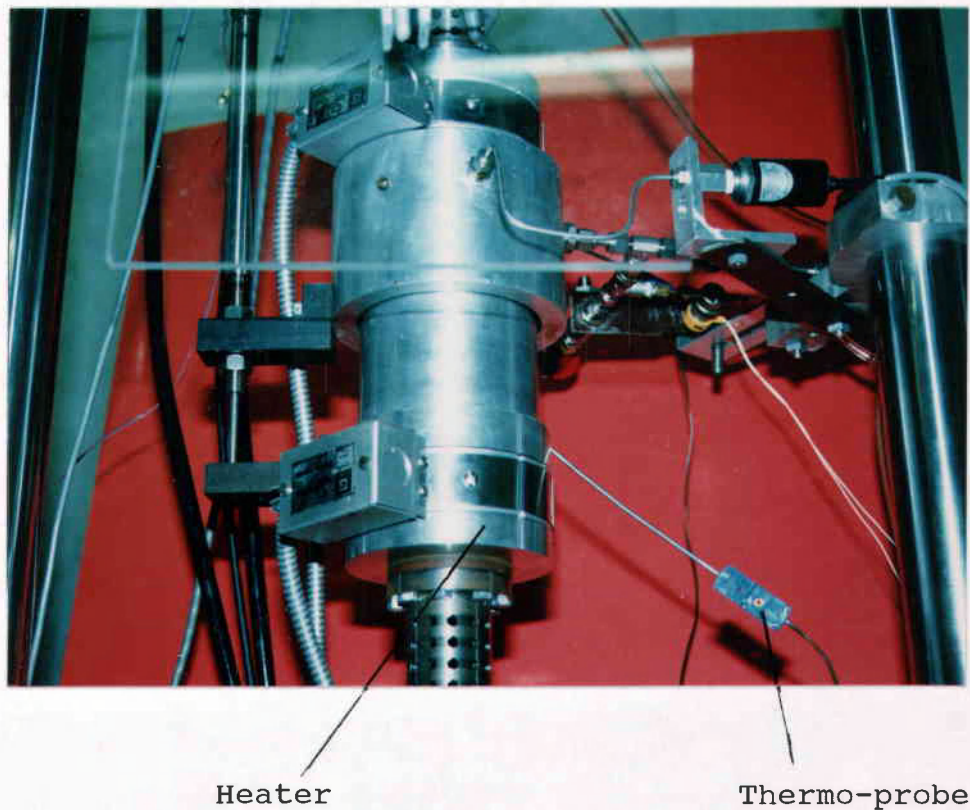
Figure. 4.10. Test system temperature measurement and control (photo).

Temperature of test system was measured by thermocouple probes inside the heated platens and controlled by the temperature controllers. In addition to measurement and control of the internal temperature of each pressing head, their interfacial temperatures between specimen and the metal were also measured during each test. This measurements were designed for control the internal temperature during each test.

High heat conductivity and capacity alloy was used to make the test system can transfer heat energy quickly, and avoid any temperature variation due to heat transfer from plates to the test specimens and to outside atmosphere.

The special designed press shell was for three dimensional temperature controlling purpose. (later we will discuss it also worked for moisture controlling purpose.)

In this way, the test system could be sealed and maintain at constant temperature condition.

4.3.2.2. Specimen temperature measurement and control

The test with steady-state condition of temperature demands the temperature uniform distributed within the sample in three dimensions. Therefore, a miniature press was designed with a relatively large annular region surrounding the pressing surfaces so that heat transfer was uniform and edge effects were minimized. The alloy shell was special

designed to cover the edge of sample to make the heat
transfer uniformly in three dimensions. A silicon rubber "O"
sealing ring was utilized here to seal the test system while
still allowing sliding motion (see Fig. 4.11).

Specimen temperatures were measured during the pre-heat
period in order to judge when uniformity have been reached
and whether it was constant during the test.

Internal temperature were measured with two
thermocouples (Type "T"). One was placed at the geometric
center of each specimen and another was positioned near the
sample / platen interface. When the center temperature was
equal to the surface temperature, then, it was assumed that
temperature was uniformly distributed throughout the
specimens and steady-state temperature had been reached.
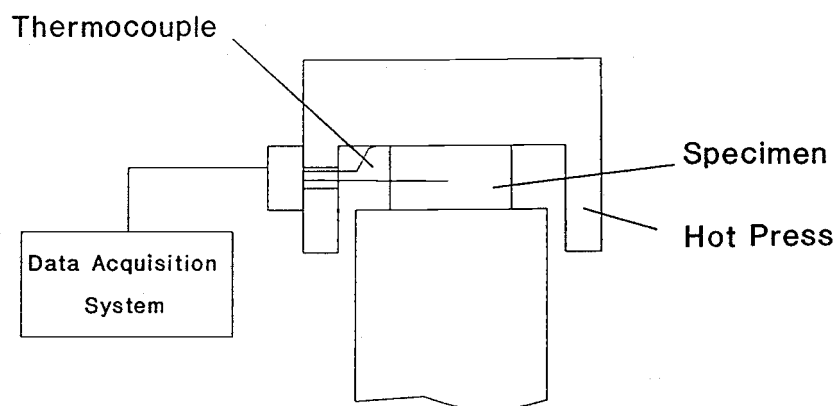
Figure 4.11. The temperature measurement system for
the specimens.

At each combined temperature and moisture conditions, two or three pre-tests were conducted to measure the temperatures of the specimens and system, and to judge how much time (average time) was needed for stability to be reached. During "real" test, only the sample / platen interfacial temperature was measured. Temperature of center of specimen was not included in "real" tests since measurement may have interfered with the thermal and mechanical behavior of the materials.

4.3.3. Specimen moisture measurement and control

Moisture condition of specimen may be measured directly, but achieving and maintaining a target value within the system is more difficult to accomplish. In many circumstance, the parameters which may be converted to calculate the moisture content were measured and controlled instead of directly control and measurement of MC.

Therefore, as pointed out earlier, the temperature and vapor pressure were the two variables used in this project to indirectly measure and control the MC of the specimens.

4.3.3.1. vapor measurement

An absolute pressure transducer was employed to measure gas pressure inside test system. Silicone oil was applied

within the connecting tube which connected the pressure
transducer to test system. This was to avoid possible water
effects on the transducer. The vapor pressures were
collected by computer data acquisition system for further
analysis. Since the test was operated under a steady-state
moisture condition, constant values of vapor pressure were
desired during each test.

Figure 4.12. shows how to measure and collect the vapor
pressure data. Since one important consideration was how to
measure it and how to separate it from residual air pressure
which was tracked inside system when hot press was closed, a
new method has been applied here to measure vapor pressure
under vacuum circumstances.
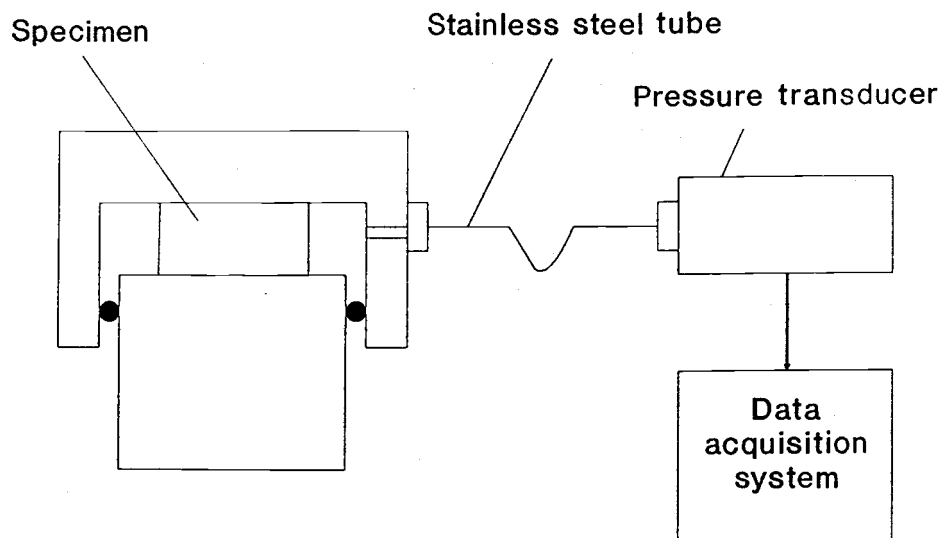
Figure 4.12. Vapor pressure measurement arrangement.

4.3.3.2. Moisture condition control

The vapor pressure measurement and control system consisted of the following main components:

1. a vacuum pump to remove most of the air from the system prior each test.

2. an electrical valve which opens or closes the test system to produce vacuum condition at beginning of each test.

3. an proportionally opening electronic servo-valve allowing excess vapor to be let out off the system to maintain the pressure at the designed values.

4. a pressure measurement and proportional feedback control circuit to enable preselected vapor pressure values to be maintained.

5. a manual adjustable safety valve for avoiding possible pressure overshooting damage or explosion.

6. a high temperature resistant silicon rubber "O" ring to seal the test system while allowing physical movement.

The vapor pressure corresponding to desired RH at prevailing temperature was pre-set on the specially constructed vapor control unit. Having carefully positioned on the lower platen, the system was sealed (by moving up the lower part of press), the electrical valve was opened, and

the internal air was evacuated. The electrical valve was then closed.

As heat was transferred into the material, the vapor pressure gradually increased. When this reached the value necessary to achieve the target RH, then the control valve opened. Excess water was ejected until isothermal condition were reached. While heat was being transferred to the center of the specimens, some moisture inevitably migrated. Time was allowed for moisture gradients to uniform prior to testing. At this time, it was assumed that the required EMC and temperature prevailed throughout the specimens.

Once the system arrived isothermal and isohygro conditions, the target vapor pressure was maintained constant value. This clearly necessitated automatic venting of vapor as the volume of the vessel decreased. When vapor pressure exceeded the pre-selected value, the control unit would proportionally open the electronic servo-valve and let the extra vapor be evacuated out by the vacuum pump until the internal pressure equaled to the preselected value. The vacuum pump was necessary because the target partial pressure of water vapor often was below atmospheric pressure(fa low MC values and / or low temperatures).

Figure 4.13. shows the process of how to measure and control vapor pressure within system.

Since a complete vacuum was impossible to achieve, there was always some residual air inside the test system

after it was closed. The pressure from the residual air also changed with temperature change (thermal expansion and contraction). However, these effects were relative small compared to the vapor pressures. In any case, they were subtracted (compensated for).
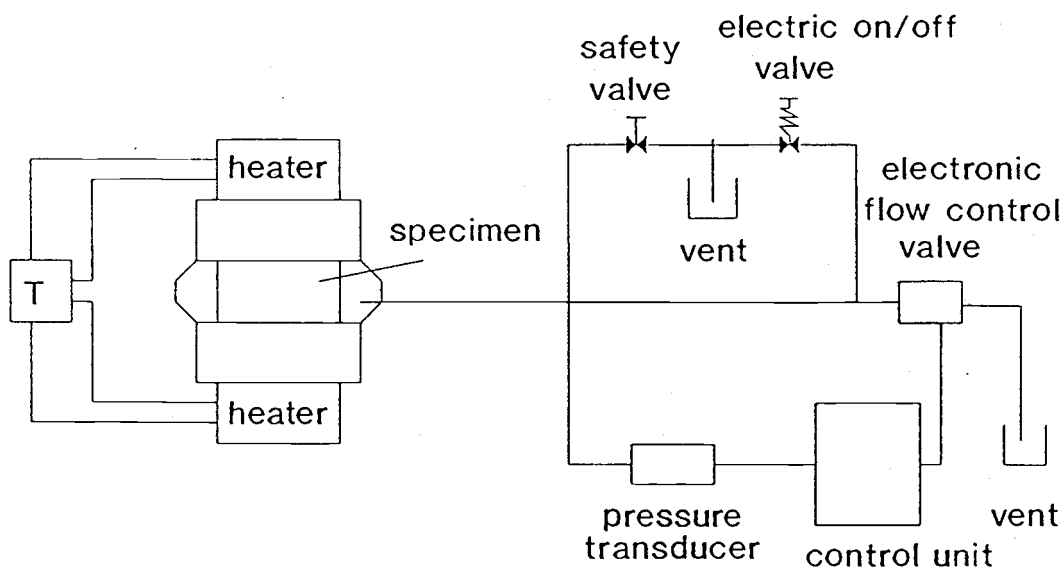
Figure 4.13. The temperature and moisture control system.

4.3.4. Computer control and data acquisition system

The physical properties of the specimens changed during each compressing test and this reacquired use of responsive control approach. A computer control and data acquisition system has been developed. This included the following functions:

1. Controlling the piston movement with load or
   position as control variables.

2. Measuring and recording the conditions of load,
   material deformation before and during each test
   cycle.

3. Collecting temperature, vapor pressure data.
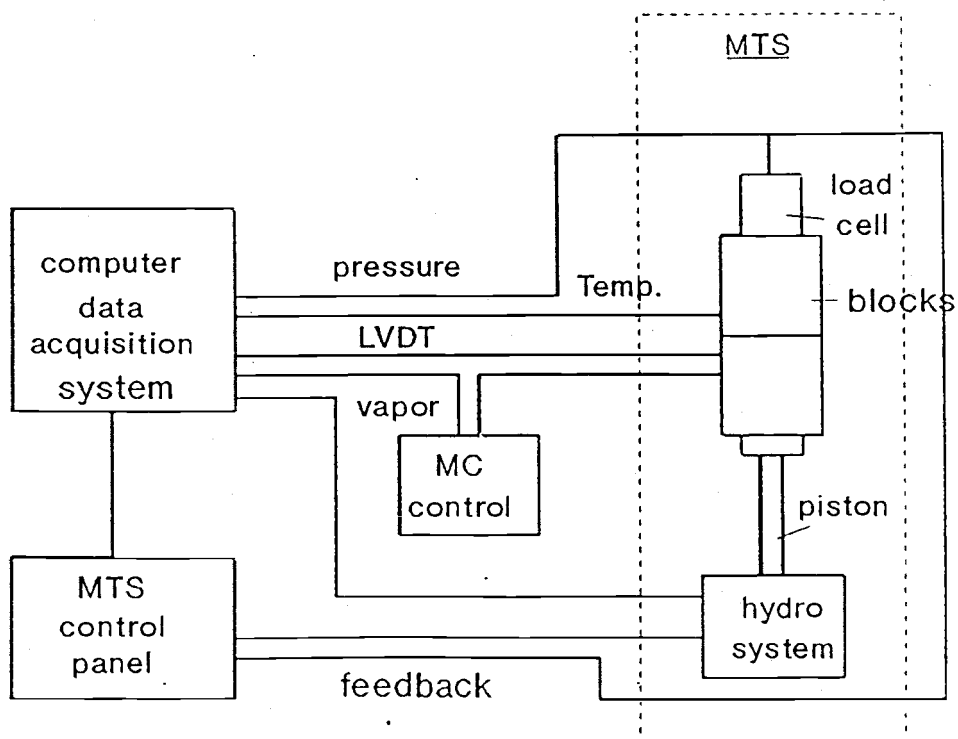
Figure. 4.14. Computer control and data collection
system.

The compression pressure and specimens deformation
which were measured by the load cell and LVDT, and the
temperatures and vapor pressure which were measured from the
thermocouple and pressure transducer were collected through

a data acquisition system, which transferred the analog data to digital data, and recorded by the computer.

4.3.5. MTS machine control

Since the original function generator of the MTS machine was not able to produce the necessary complex serial control curves, a computer control system was designed to replace the original function generator of MTS and to enhance the performance of the machine.

After the computer control system was incorporated, the complicated press behavior could be programmed via a PC.

Figure 4.15. shows the complete test system.
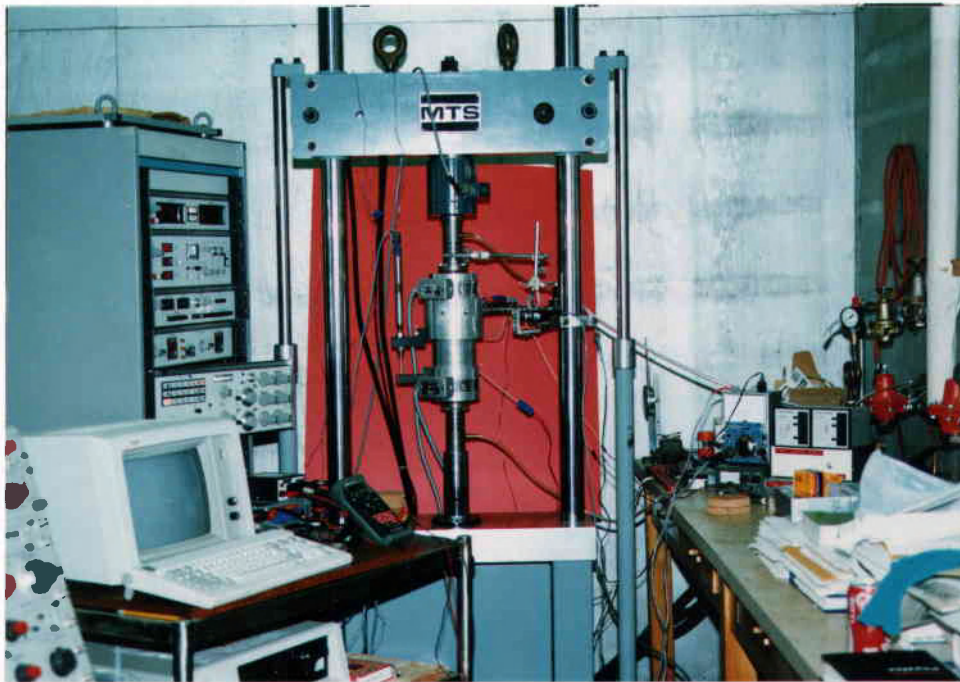
Figure 4.15. A complete test system (photo).

4.4. Experimental test sequence

Circular specimens 90 mm diameter and 25 mm thick were put in several conditioning rooms to achieve the required wood moisture contents. Following pre-treatment, the specimen was immediately placed in the test system, and the temperature and vapor control systems were adjusted to the required values. The miniature press was first closed to a pre-determined position where the two parts of the press just touched the bottom and top surface of the specimen. This position was maintained for the duration of the pre-treatment period. In this way, the specimen usually quickly reached the required steady-state temperature. At the same time, water vapor was generated. The vapor pressure and temperature were increased around the specimens.

The flexible silicon rubber "O" seal ring kept the system insulated for controlling the environment at each test. When the target pre-selected hot pressing condition was approached, the electronic valve was activated by the vapor controlling system which functioned depending on the signal from vapor pressure transducer which measures the system vapor condition. During each test, the deformations of the materials were measured in response to the load control cycle.

Repetition of this procedure for different pressing conditions enabled the rheological characteristics of the

specimens during steady-state temperature and moisture conditions to be evaluated. New specimens were prepared for each test. Results were specific to the material, temperature, moisture content and mean platen pressure used for each test.

CHAPTER 5. DATA ANALYSIS

5.1. Determination of rheological properties

The following should be regarded as a preliminary attempt to derive rheological models for the materials. In order to determine the rheological properties, recall the definition of the proposed rheological model (equation 3.3):

$$\sigma + \left(\frac{\frac{K_1}{E_1 PMF}}{E_1 + PMF} + \frac{K_1 + K_2}{E_2} \right) \frac{d\sigma}{dt} + \left(\frac{K_1 K_2}{\frac{E_1 PMF}{E_1 + PMF} E_2} \right) \frac{d^2\sigma}{dt^2} = K_1 \frac{d\varepsilon}{dt} + \frac{K_1 K_2}{E_2} \frac{d^2\varepsilon}{dt^2}$$

For wood composite materials under conditions of compression:

$$\varepsilon = \frac{\sigma}{E_1} + \frac{\sigma}{PMF} + \frac{\sigma t}{K_1} + \frac{\sigma}{E_2} \left(1 - e^{\left(\frac{-E_2 t}{K_2} \right)} \right) \qquad (5.1)$$

where, E1 : elastic element (EE1) property (Pa) response to instantaneous elastic behavior.

K1 : viscous element (EV1) property (Pa * sec) response to irreversible viscous behavior.

PMF: plastic-fracture element (EPMF) property (Pa) response to fracture and plastic behavior during compression.

E2 : elastic element (EE2) property (Pa) response to delayed elastic behavior.

K2 : viscous element (EV2) property (Pa * sec) response to delayed elastic behavior.

t : time (sec)

σ : stress (Pa)

ϵ : strain (mm/mm)

Determination of these properties requires an analysis of the rheological behavior and related mathematical description, which has been discussed earlier. A physical-mathematical method has been developed here for doing this work.

The following assumptions have been made:

1. Specimen structures and properties are continuously and uniformly distributed throughout.

2. Rheological properties may change as the micro-structure changes and this is directly related to the prevailing density of the materials (an important assumption discussed earlier).

3. The dimensions of the specimens only change in the direction of thickness. The variation of diameter (poisson's effect) is relatively small (due to the porous nature of the network) and will be neglected.

5.1.1. Overall strategy for finding elements' properties

Figure 5.1 shows a section of a typical test curve. The properties of each of the five elements have been inferred by judicious interpretation of deformations resulting from specific parts of the loading cycle.
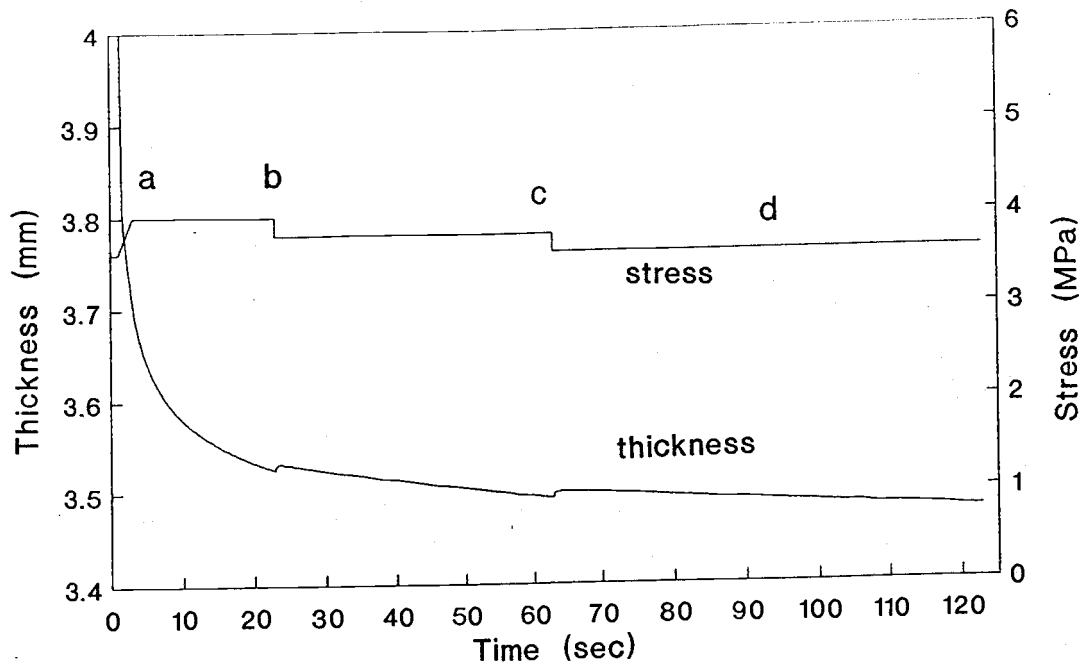
Figure 5.1. A section (part I) of a typical test curve for deriving rheological constants.

a. The values of E1 and K1 can be directly calculated from the relationship of stress and strain of each test result. The relationship between these constants and density (element property = f (ρ), where, ρ = density), then, can be established by mathematical or statistical methods from a group of test results.

b. Applying the equation of E1 to separate PMF (plastic and fracture characteristics) from each test result, and then, evaluating the PMF component as a function of density.

c. Applying the equations of E1, PMF and K1 to get the E2 values in each test result, and evaluating E2 as a function of density from the group of test results (for different P values).

d. Applying the equations of E1, PMF, K1 and E2 to obtain the K2 values in each test result, and evaluating K2 as a function of density from the group test results.

In this way, the relationships between the element's properties and the material's density may be established. More details of how to get those constants and how to find the equations will be discussed in the following sections.

5.1.2. Process for evaluating E1

During the first part of each test, compressive pressure is reduced twice (see Figure 5.1. points b and c), though the pressure is only reduced by a very small amount (the difference is 5 % of the average load during section I of the loading cycle). During these rapid unloading stages, the specimens undergo two instantaneous relaxation (expansion) responses, which, to first approximatise, only involve instantaneous elastic deformation of EE1. Values are specific to the average density that prevailed during the unloading period (which was almost instantaneous) and it follows that:

at point b:
$$\Delta\sigma_b = \sigma_{b1} - \sigma_{b2}$$
$$\epsilon_b = (\text{thickness}_{b1} - \text{thickness}_{b2}) / \text{thickness}_{b1}$$

$$E1_b = \frac{\Delta\sigma_b}{\epsilon_b} \qquad (5.2)$$

at point c: (same as above)

$$E1_c = \frac{\Delta\sigma_c}{\epsilon_c} \qquad (5.3)$$

A number of elastic properties are obtained from a group of tests conducted under a range of mean compressing pressures (1, 2, 4, 6 MPa), specific densities (related to thickness) and steady-state conditions of temperature and moisture (points on Fig.5.2). Each test condition was repeated two to three times.

A regression equation based on the data which is presented in Figure 5.2. then, is generated; this curve is superimposed on the data in figure 5.2.

$$E1 = e^{A+B\rho} \qquad (5.4)$$

where, A and B: constants
ρ : density

The regression equation represents the variation of E1 with density while the material is at a specified thermo-hygro state, and this establishes the constitutive relationship between E1 and density.
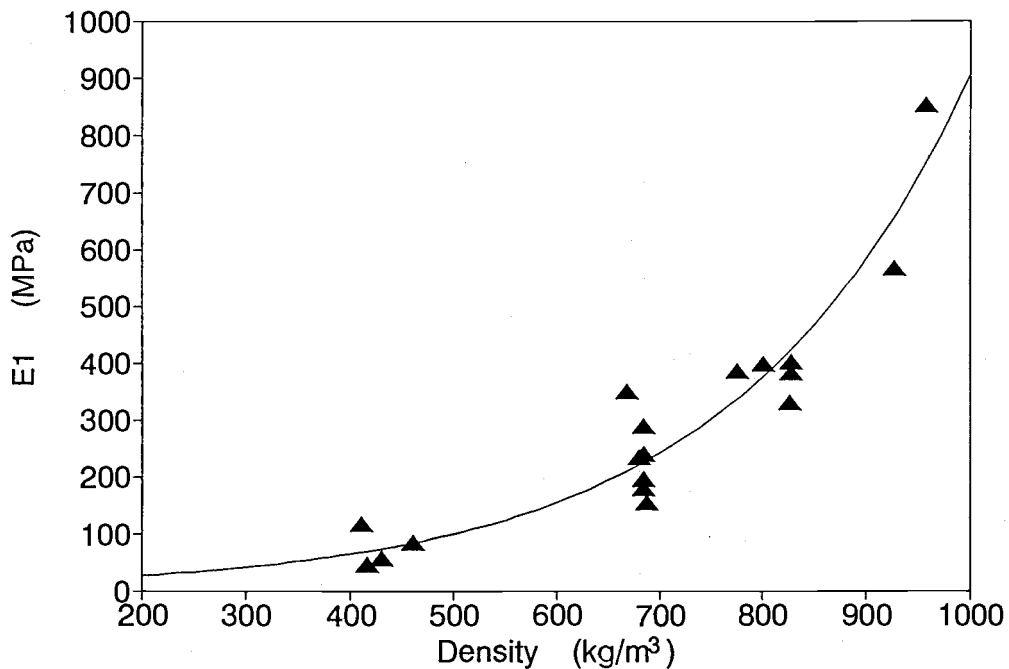
Figure 5.2. E1 vs density for a typical test condition (T = 100 °C, MC = 4%).

It is necessary to be aware that the above established work assumes plastic, delayed elastic and viscous types of behavior do not take place during the short time periods while the load decreases and resultant thickness increases occur at points of b and c. Though some of the elemental effects must in fact occur, they are likely to be small enough to be neglected (at least in the first analysis). Hence the deformations at points b and c are assumed to be caused only by the effects of EE1.

It will also be assumed that interactions among the five elements do not occur or significantly effect the

accuracy of the present work. However, such interactions may prove to be necessary in future refinement of the models.

5.1.3. Process for evaluating PMF

During the initial stage of the compressive pressure increase, rapid stress increases (Figure 5.3) produce localized structural failures and micro-structural relocation, as well as elastic deformation. It is assumed that the instantaneous elastic deformation, fiber fractures and relocation happen as a direct consequence of compression (the applicaiton of pressure) at each step of stress increase.
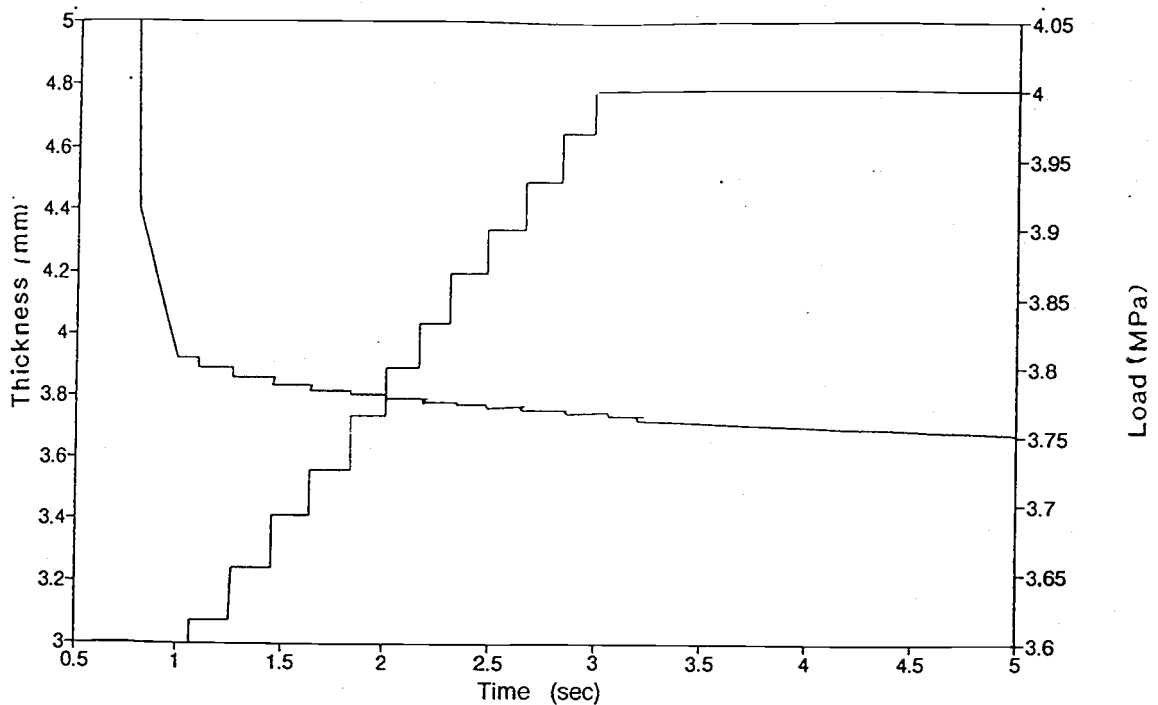
Figure 5.3. Initial stage of compression for quantifying PMF.

Since the effects of EV1, EE2/EV2 are assumed to be small enough to be neglected at each stepwise stress increase, the strain due to both EE1 and EPMF behaviors at each density condition (thickness) is given by:

$$\varepsilon_{instant.} = \varepsilon_{elastic} + \varepsilon_{PMF} \qquad (5.5)$$

Differences in responses during instantaneous load increases and decreases may be used to distinguish between elastic and fractural mechanisms. A method is developed here to separate the EPMF and EE1 properties at this initial stage of compression. We subtract the strain of EE1 from the total instantaneous strain so that the strain of EPMF may be calculated as a consequence of a rapid load change. Therefore, when loads increase almost instantaneously, strain of EE1 can be calculated:

$$E1 = e^{A+B\rho}$$

$$\varepsilon_{EE1} = \frac{\Delta\sigma}{E1} \qquad (5.6)$$

PMF can then be quantified:

$$PMF = \frac{\Delta\sigma}{(\varepsilon_{instant} - \varepsilon_{PMF})} \qquad (5.7)$$

Different PMF values also are derived from groups of test results based on density, the same as when calculating E1. Figure 5.4. presents values for the property of plastic-micro-fractural element with the density and a regression curve (PMF = $e^{A+B\rho}$) resulting from those data.

A relationship between the instantaneous plastic behavior and the material density then is established.
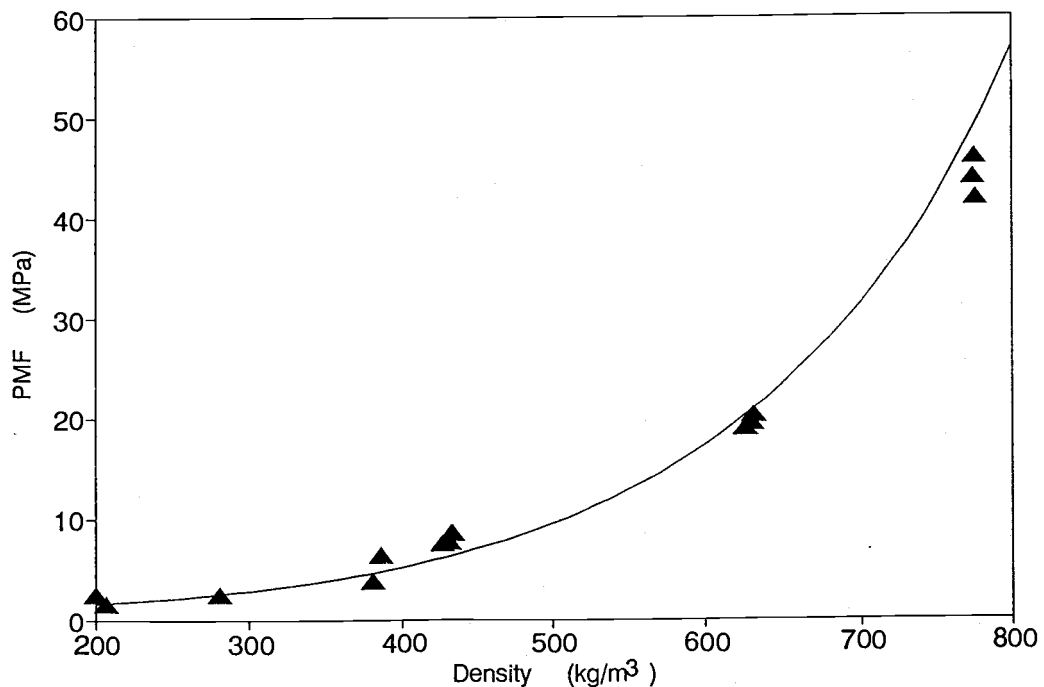
Figure 5.4. PMF vs density data and an exponentially fit curve for a typical test condition (T = 100 °C, MC = 4%).

5.1.4. Process for evaluating K1

Let us first consider EV1's behavior. It is observed that during a period of sustained stress, the deformation continuously varied (Figure 5.1. stage d).

$$\varepsilon_{EE2/EV2} = \frac{\sigma}{E2} e^{-\frac{E2t}{K2}}$$

(5.8)

if $t \to \infty$, then, $\epsilon_{EE2/EV2} \to 0$

If time is long enough, the deformation of EE2/EV2 is apparently so small with increasing time that its effect may be neglected. The deformation of EE2/EV2 is approximately zero and it follows that:

$$\varepsilon = \frac{\sigma}{E_1} + \frac{\sigma}{PMF} + \frac{\sigma t}{K_1} + \frac{\sigma}{E_2}$$

(5.9)

A method has therefore been developed to divide the behavior of EV1 from that of the other elements. The slope of the thickness versus time curve (Fig. 5.1. d) is represented by the following equation:

$$\frac{\varepsilon}{\Delta t} = \frac{\sigma}{K1}$$

(5.10)

where, ϵ = (thickness$_1$ - thickness$_2$) / thickness$_1$
Δt = time$_1$ - time$_2$

The property of EV1 is therefore given by:

$$K_1 = \frac{\sigma \Delta t}{\varepsilon}$$

(5.11)

Different K1 values based on different densities can be derived from groups of test results by applying a range of compressing pressures while the specimen is under constant and similar environmental condition. Figure 5.5 shows the K1 versus density relationship, and a regression curve for those data (K1 = $e^{A+B\rho}$).
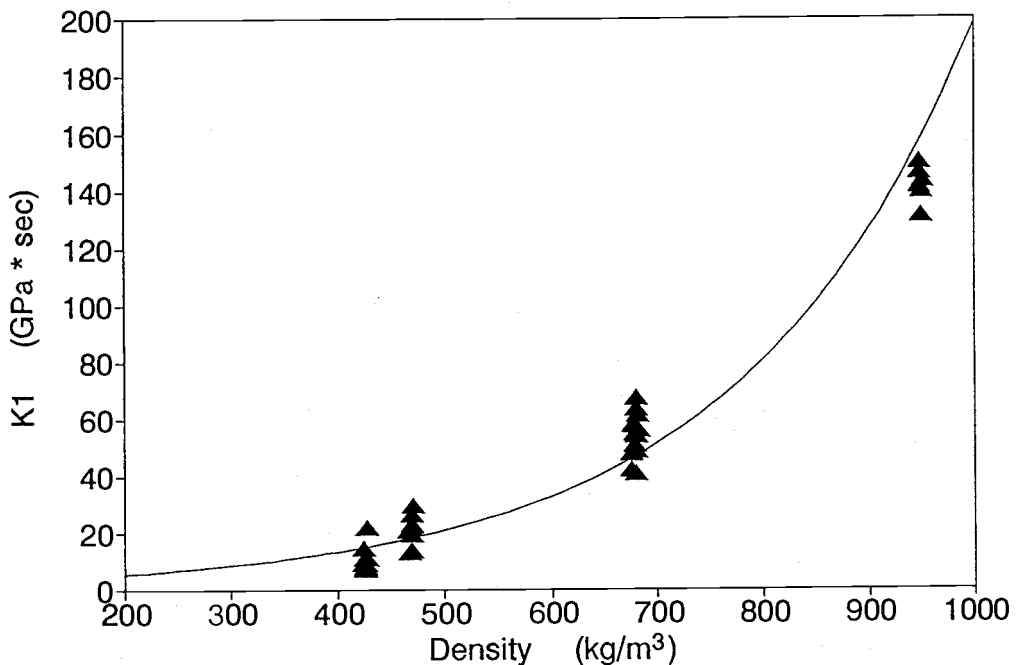
Figure 5.5. K1 vs density data and an exponentially fitted curve for a typical test condition (T = 100 °C, MC = 4%).

5.1.5. Process for evaluating E2

As we discussed in the previous section, at that part of the curve (Fig. 5.1. d) from which the K1 value is derived, the effect of EV2 is so small that its contribution to the total behavior appears to become insignificant. Therefore, if we could carefully calculate the other elemental deformations accumulated at this stage, the delayed elastic deformation will be approximately equal to the deformation of element EE2 (since the $\epsilon_{EE2/EV2} = 0$). The strain can be described by the following equation:

$$\varepsilon_{total} = \varepsilon_{EE1} + \varepsilon_{PMF} + \varepsilon_{EV1} + \varepsilon_{EE2} \tag{5.12}$$

We subtract the strains of EV1, EE1 and EPMF from the total strain to obtain the strain of EE2, and then calculate a value of E2.

In this procedure, the cumulative contribution of EV1 under changing density values (and EV1 values) must be taken into account.

$$E2 = \frac{\sigma}{\varepsilon_{EE2}} \tag{5.13}$$

Again, the effect of density on E2 may be explored by conducting tests under a range of mean loading values (P). Figure 5.5 shows such a set of E2 values and a regression curve (E2 = $e^{A+B\rho}$) based on those data.
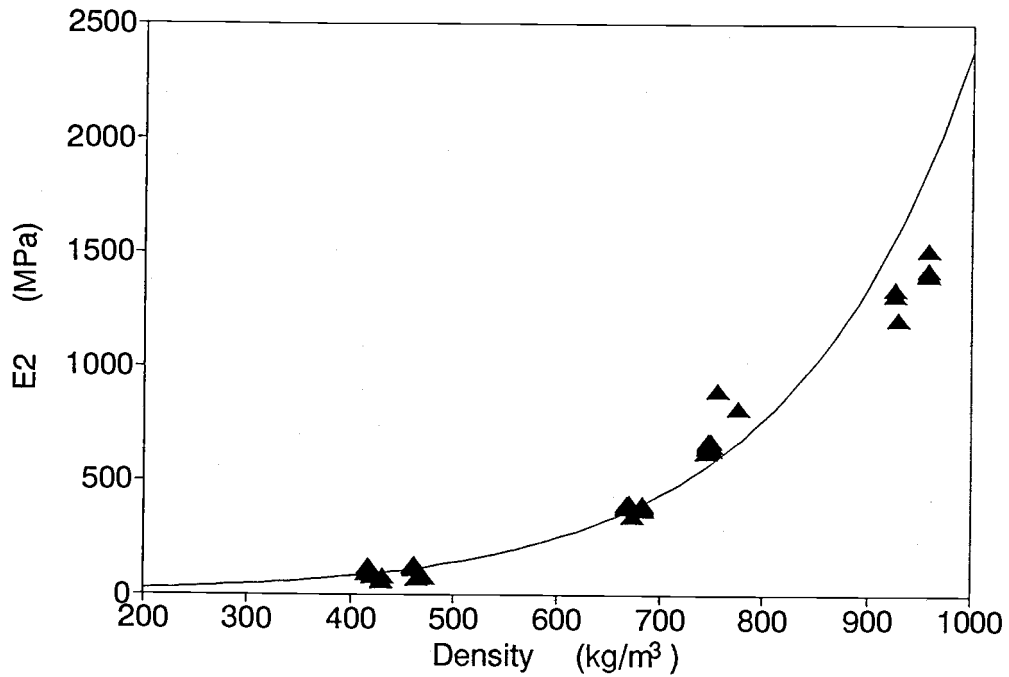
Figure 5.6. E2 vs density data and an exponentially
            fitted curve for a typical test condition
            (T = 100°C, MC = 4%).

5.1.6.   Process for evaluating K2

Since the other four elemental properties (E1, PMF, K1 and E2) have been quantified, the deformation of EV2 may be approximated as the result of the deformations of other elements subtracted from the total deformation. Therefore, the strain of EV2 can be quantified by the following equation:

$$\varepsilon_{EE2/EV2} = \varepsilon_{total} - \varepsilon_{EE1} - \varepsilon_{PMF} - \varepsilon_{EV1} - \varepsilon_{EE2} \tag{5.14}$$

Since deformation of EE1, EPMF, EV1 and EE2 can be calculated, the strain of EE2/EV2 is given by:

$$\varepsilon_{EE2/EV2} = \frac{\sigma}{E2}\left(e^{\frac{-E2t}{K2}}\right) \tag{5.15}$$

The value of K2 can be quantified from the following equations:

$$Ln\varepsilon_{EE2/EV2} = Ln\left(\frac{\sigma}{E2}\right) - \frac{E2t}{2.3K2}$$

$$K2 = \frac{E2t}{2.3\left[Ln\left(\frac{\sigma}{E2}\right) - Ln\varepsilon_{EE2/EV2}\right]} \tag{5.16}$$

By applying the same procedure as those for the other elemental properties, a group of experimental data can be used to establish the relationship between the K2 and density. Figure 5.6 represents the values of K2 and a regression curve (K2 = $e^{A+B\rho}$) based on these values.
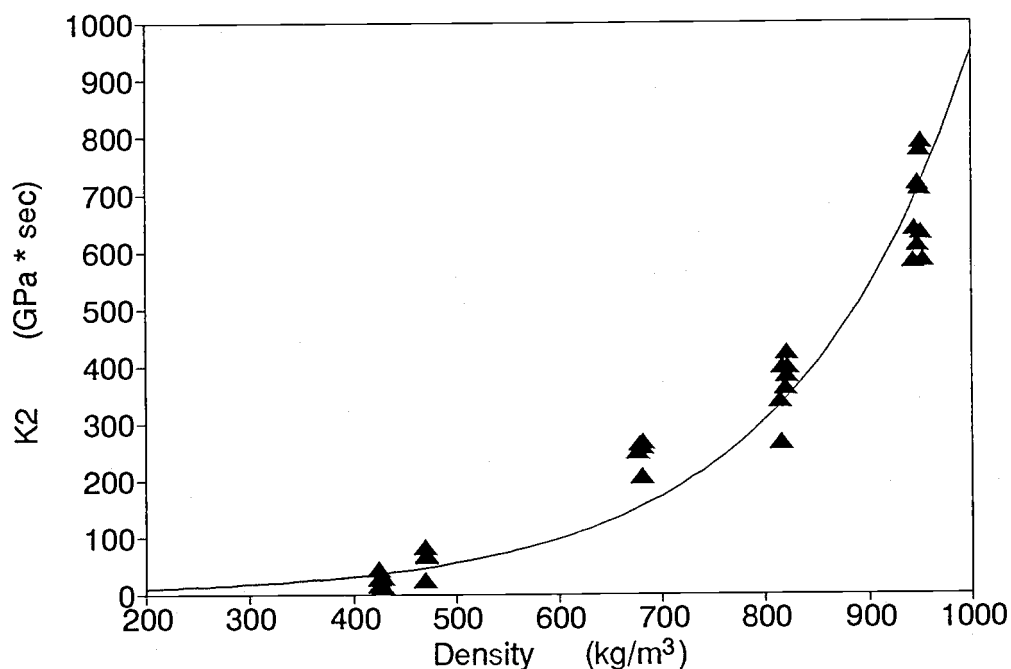
Figure 5.7. K2 vs density data and an exponentially
fitted curve for a typical test condition
(T = 100 $^{\circ}$C, MC = 4%).

Figure 5.8. shows how all five elements vary with

density under a typical isothermo-hygro condition. The

complete information of the whole range of temperature and

moisture conditions investigated, and the nonlinear

regression results are presented in Appendix II.
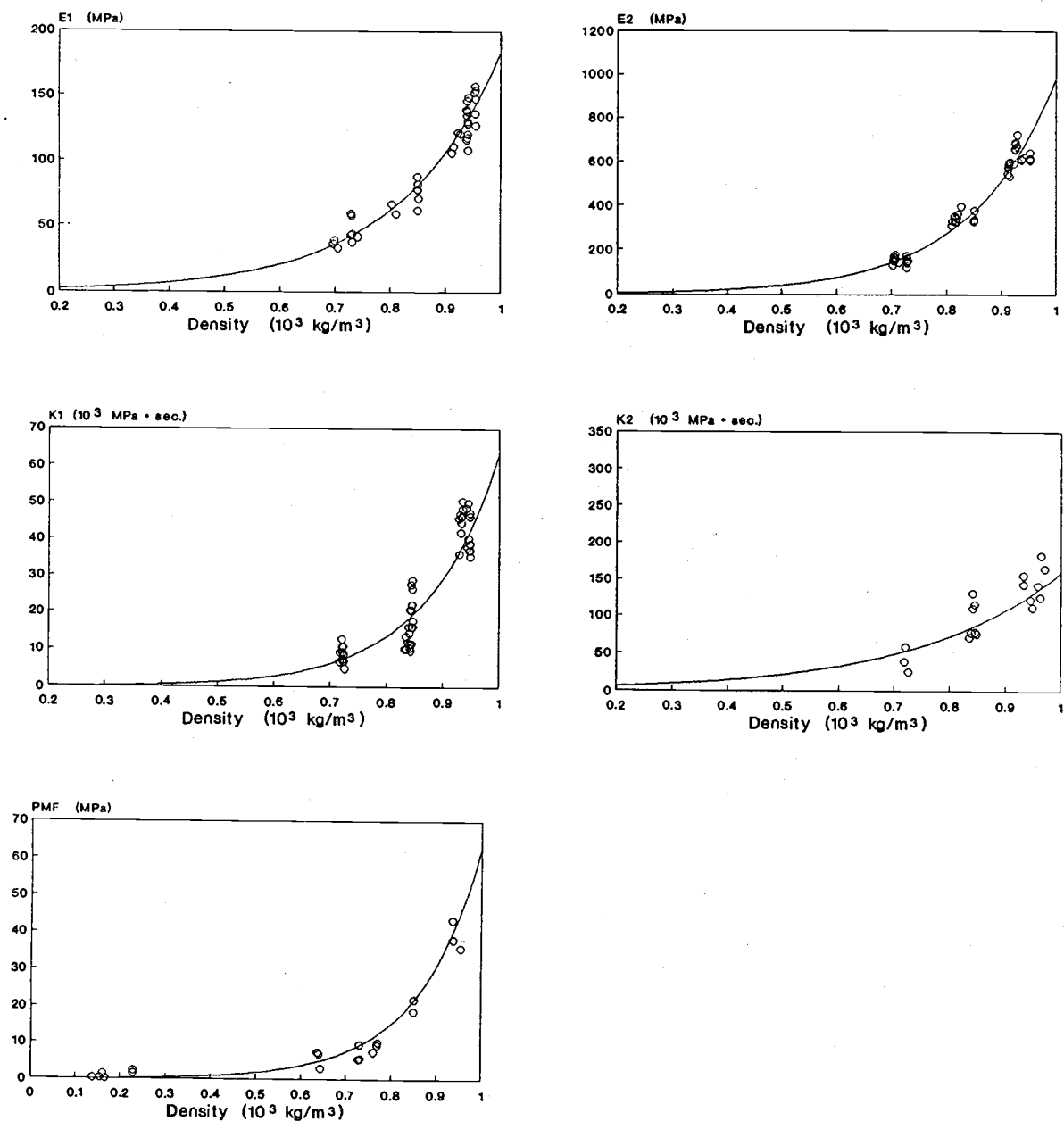
Figure 5.8. One example of the five constants vs
density (T = 150 °C, MC = 16 %).
(see Appendix II for the whole set).

5.2. Determination of thermo-hygro-effects

Having derived an approach to obtain relationships between the density and the rheological properties of materials under specific thermo-hygro conditions, the effects of temperature and moisture conditions on the rheological properties then, can be quantified by repeating this procedure. Figure 5.9 and Figure 5.10 demonstrate how the properties of five elements are effected by temperature and moisture content (complete information is given in Appendix II). Further discussion about thermo-hygro-effects is given in chapter 7.
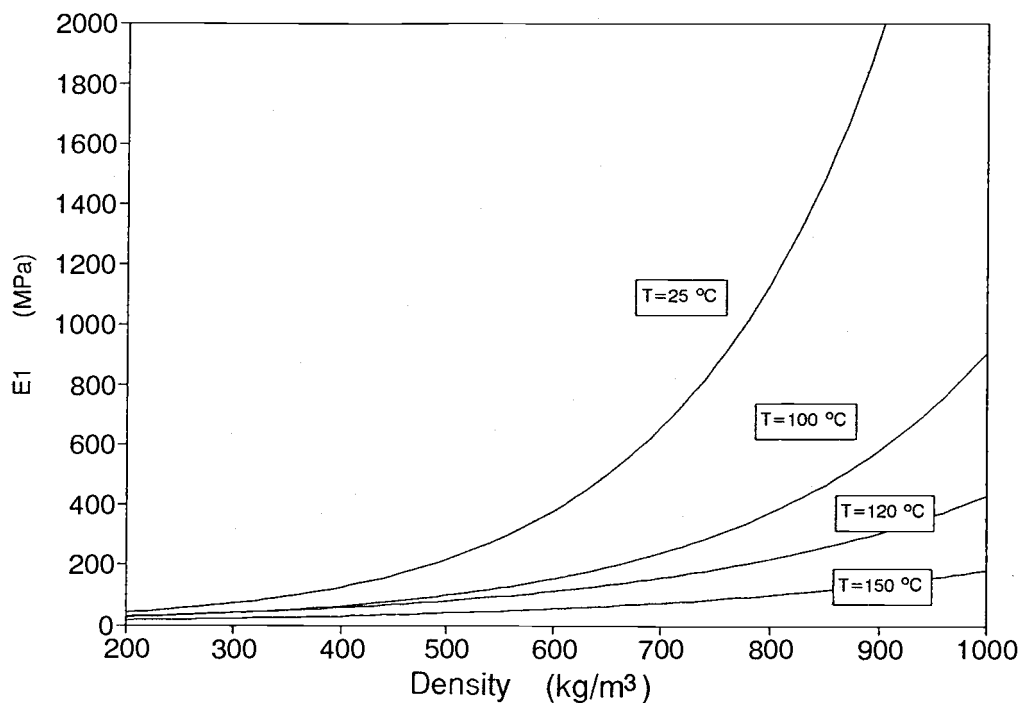
Figure 5.9. The effects of structure (density) and temperature on EE1.
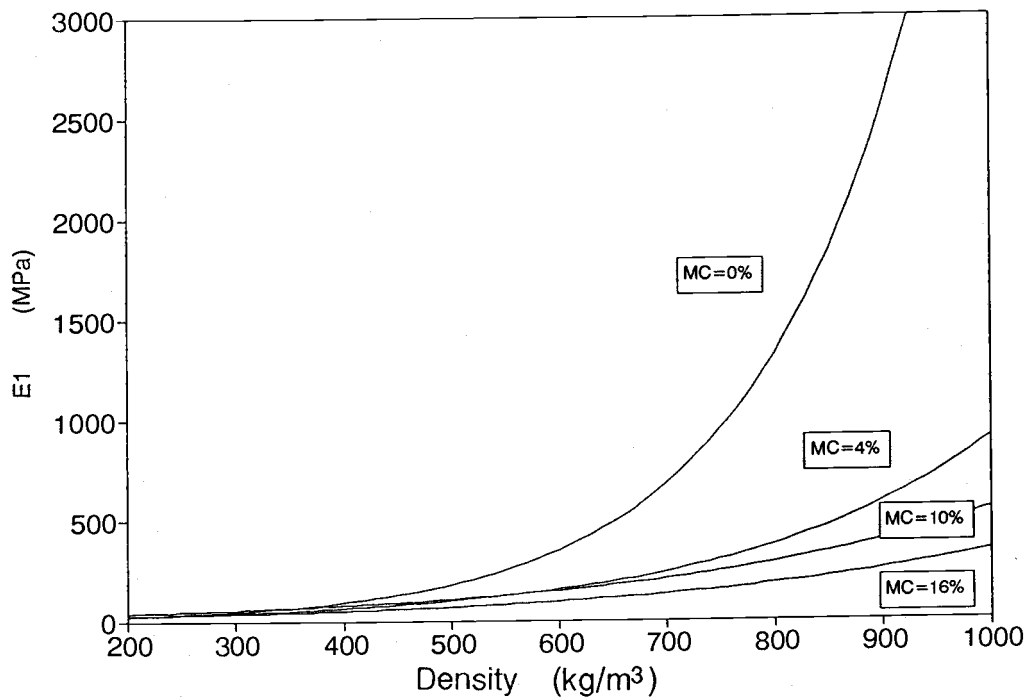
Figure 5.10. The effects of density and moisture on
EE1.

Table 5.1 summarizes the results of regression analysis
of the element's behavior with density, temperature and
moisture conditions. Complete regression analysis results
are given in Appendix III.

Table 5.1. How the five elements are effected by
density, temperature and moisture content.

EE1 = EXP (A + B *ρ)

Temp. °C	MC %	R	A	B
5	0	0.964	2.72063	0.006364
100	0	0.946	2.65174	0.005479
120	0	0.912	2.59871	0.00553
150	0	0.914	2.33204	0.005544
25	4	0.904	1.88442	0.00662
100	4	0.950	2.39771	0.004411
120	4	0.864	3.05273	0.003255
150	4	0.866	2.63164	0.00321
25	10	0.932	1.79215	0.006473
100	10	0.808	2.73551	0.003331
120	10	0.783	1.68379	0.004109
150	10	0.841	-2.0938	0.008054
25	16	0.940	2.47814	0.003677
100	16	0.919	2.22265	0.002998
120	16	0.754	2.25415	0.002787
150	16	0.956	-0.21987	0.005431

(Table 5.1. continued)

EPMF = EXP (A + B *ρ)

Temp. °C	MC %	R	a	b
25	0	0.888	−0.50492	0.008332
100	0	0.887	−0.85454	0.008572
120	0	0.913	−0.99294	0.007296
150	0	0.901	−1.26273	0.007391
25	4	0.888	−1.37924	0.009034
100	4	0.925	−0.7362	0.005974
120	4	0.894	−1.15077	0.006281
150	4	0.903	−0.39131	0.004438
25	10	0.882	−0.71583	0.00683
100	10	0.948	−0.94233	0.005706
120	10	0.947	−0.6012	0.005182
150	10	0.981	−4.58683	0.011842
25	16	0.963	−0.20318	0.004803
100	16	0.924	−0.72868	0.005008
120	16	0.829	−0.86604	0.004606
150	16	0.814	−2.94695	0.007086

EV1 = EXP (A + B *ρ)

Temp. °C	MC %	R	A	B
25	0	0.976	7.03929	0.008572
100	0	0.918	7.05826	0.006731
120	0	0.938	6.72563	0.006975
150	0	0.899	6.58855	0.006413
25	4	0.986	7.2095	0.006741
100	4	0.917	7.69316	0.004504
120	4	0.943	6.8686	0.005591
150	4	0.945	5.44764	0.006515
25	10	0.957	6.99715	0.006353
100	10	0.929	6.97595	0.004208
120	10	0.862	4.95519	0.006469
150	10	0.874	2.09287	0.00956
25	16	0.967	7.3551	0.004358
100	16	0.972	5.4637	0.005804
120	16	0.962	2.94444	0.008896
150	16	0.920	3.31537	0.007739

(Table 5.1. continued)   111

EE2 = EXP (A + B *ρ)

Temp. °C	MC %	R	A	B
25	0	0.989	2.09391	0.008599
100	0	0.974	2.0031	0.007899
120	0	0.968	1.76593	0.00736
150	0	0.958	1.29433	0.007898
25	4	0.969	1.50248	0.008205
100	4	0.975	2.10239	0.005674
120	4	0.955	2.76024	0.005139
150	4	0.952	1.96528	0.00523
25	10	0.972	1.94875	0.007296
100	10	0.985	2.27419	0.004879
120	10	0.985	3.19372	0.003712
150	10	0.933	-0.88903	0.011727
25	16	0.952	2.56073	0.00484
100	16	0.985	1.47303	0.005417
120	16	0.941	2.60589	0.003975
150	16	0.981	0.45006	0.006443

(Table 5.1. continued)

EV2 = EXP (A + B *ρ)

Temp. °C	MC %	R	A	B
25	0	0.940	7.71583	0.010469
100	0	0.949	7.14709	0.009689
120	0	0.920	8.13388	0.006967
150	0	0.979	4.82398	0.011632
25	4	0.972	6.67971	0.010772
100	4	0.951	8.06327	0.005701
120	4	0.928	6.86583	0.006274
150	4	0.900	6.61729	0.006925
25	10	0.962	5.89206	0.012053
100	10	0.943	6.81938	0.006213
120	10	0.916	6.26179	0.006568
150	10	0.876	5.74813	0.005891
25	16	0.963	7.48219	0.006749
100	16	0.907	5.97159	0.00699
120	16	0.897	6.52881	0.005758
150	16	0.867	7.99562	0.003984

CHAPTER 6. RESULTS AND DISCUSSION I

--Preliminary evaluation of the model--

Following establishment of the rheological model and quantification of the rheological parameters of the tested materials (from experimental results), it is necessary to find if the model logically and usefully represents the material's behavior. Only a preliminary evaluation is presented in this chapter since the main focus of the research was development of the experimental techniques.

6.1. Evaluation of the physical principles of the model

The relations between stress and strain:

Figure 6.1. shows an example of load-deformation relation predicted by the model. With a given loading cycle, the deformation continuously varies.

Since the structure and associated properties of wood composite materials during compression varies continuously, the deformations are not only time dependent but also structure dependent.
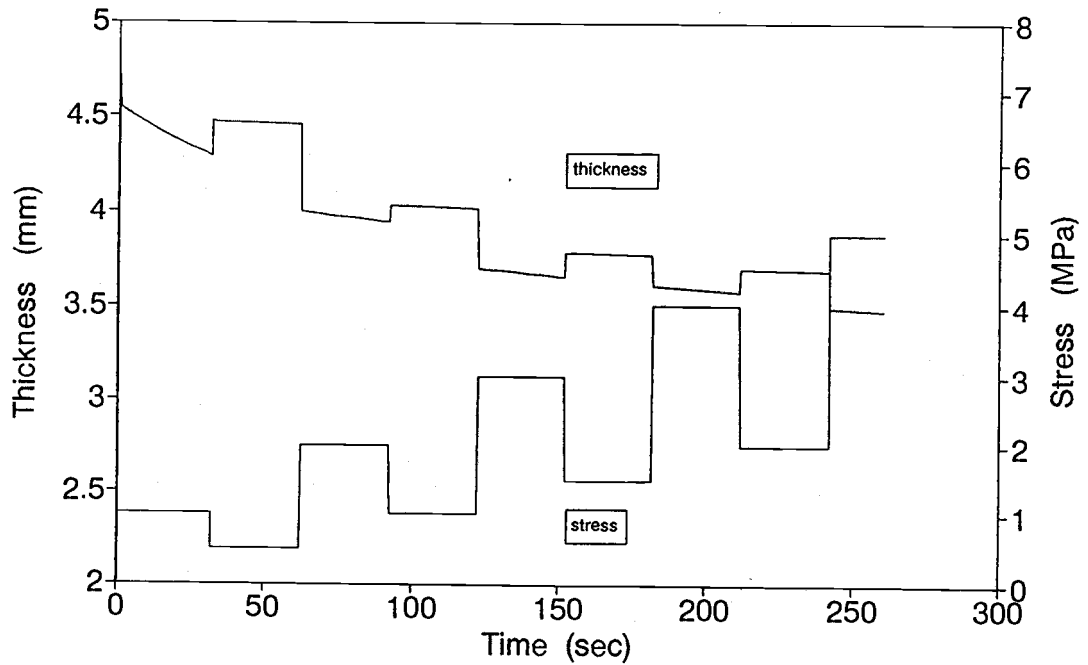
Figure 6.1. Predicted thickness versus time curve for
         a given load curve.

Temperature effects:

It is well known that the wood materials are easily

softened and deformed under high temperatures. Figure 6.2.

shows deformation curves predicted by the model under

different isothermal conditions when the moisture content

was held constant. As expected, the higher deformations were

predicted under the higher temperature conditions (Fig. 6.2.

curve of 120 °C).
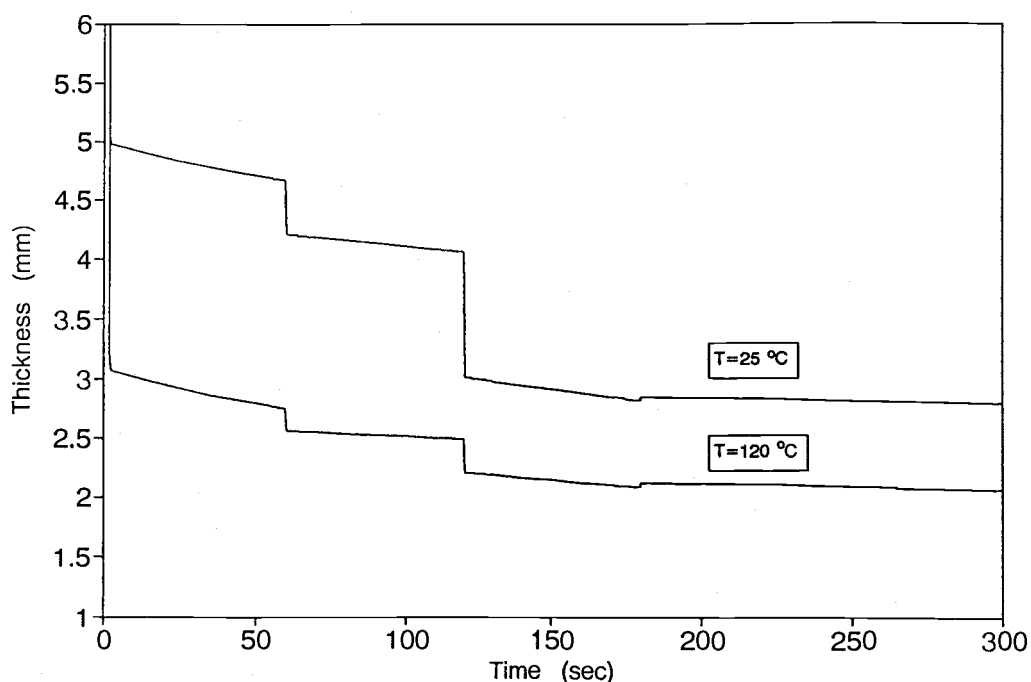
Figure 6.2. Typical predicted temperature effects on
rheological deformation (MC = 4 %).

Moisture effects:

Moisture effects on the mechanical behavior are a

little more complex than those for temperature. However,

under high moisture conditions, the thermal effects are

quite obvious. The higher moisture contents make the

materials more easily relocated and deformed — as would be

expected from well known effects of cell wall moisture on

properties. From the predicted curves in Figure 6.3, the

effects of the moisture were observed when the temperature

was held constant.
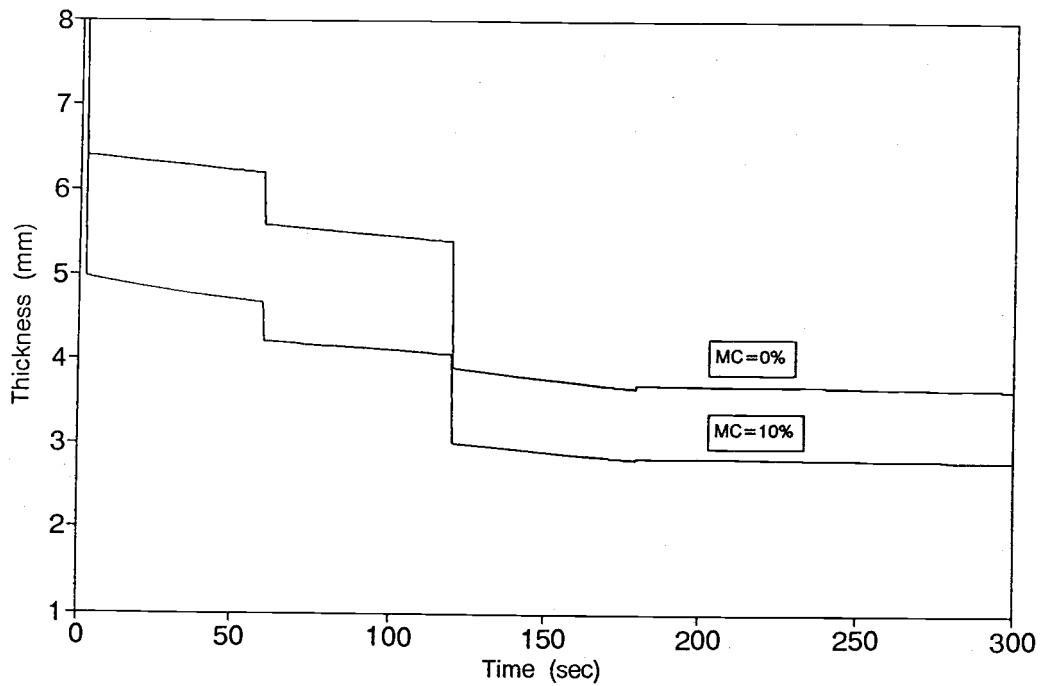
Figure 6.3. Typical predicted moisture effects on
deformation (T = 100 °C).

6.2. Rheological parameters

Figure 6.4. suggests that some of the derived
rheological properties are logically dependent on density.
Furthermore, for example, Figure 6.5 shows that the E1
values increase with density, but temperature reduction
coupled with moisture increase causes the E1 curve to shift
downward.

According to the values of these parameters and the
rheological model discussed in chapter 3 and 5, elements of
EE1 and EPMF are more sensitive than the other elements

during the initial stages of the compression cycle. With
time increases, the sensitivity of EE2 increases while that
of EV2 decreases. EV1's influence is relatively small over
the times of concern here. Since this is a preliminary
evaluation, a complete range of tests have not been
conducted here.
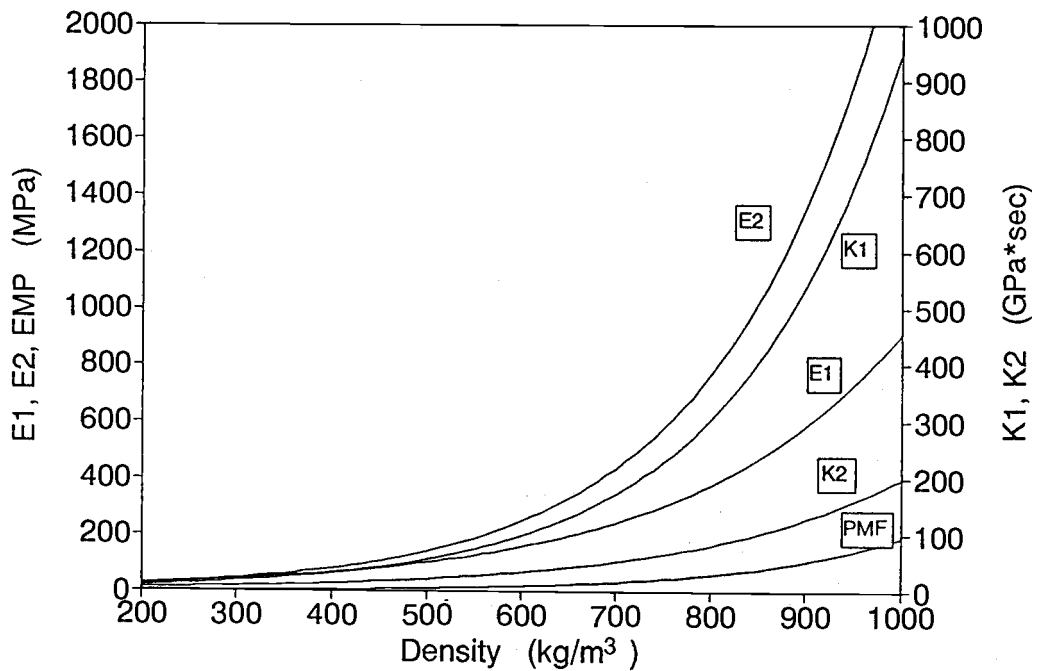
Figure 6.4. Typical variation of the five elements with
density (T = 100 $^\circ$C, MC = 4%).
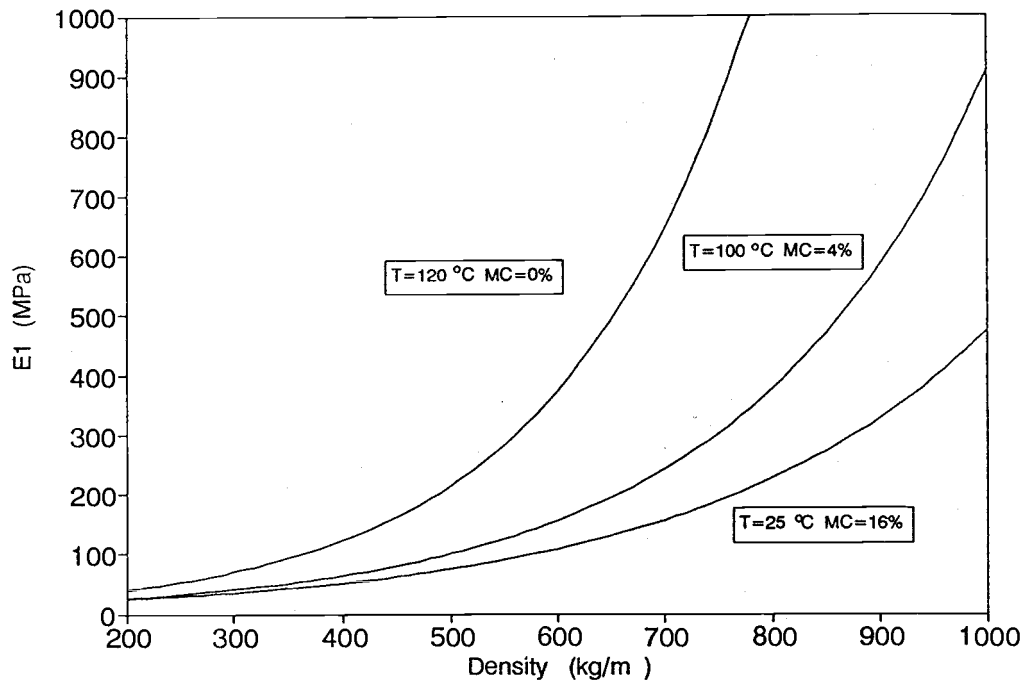
Figure 6.5. Typical variation of E1 under different
temperature and moisture conditions.

6.3. General evaluation of the model

Absolute evaluation of accuracy of the elements is
difficult in the absence of supporting literature.
Comparisons will therefore be made between predicted and
experimentally measured behavior for a range of dynamic
loading cycles.

Figure 6.6. shows specially designed experimentally
executed loading and corresponding deformation curves,
together with the deformation curve predicted by the model.

The difference between the two curves reflects the
quality of the model. Discrepancies are generally relatively
small and will be discussed in a little more detail in
following sections.
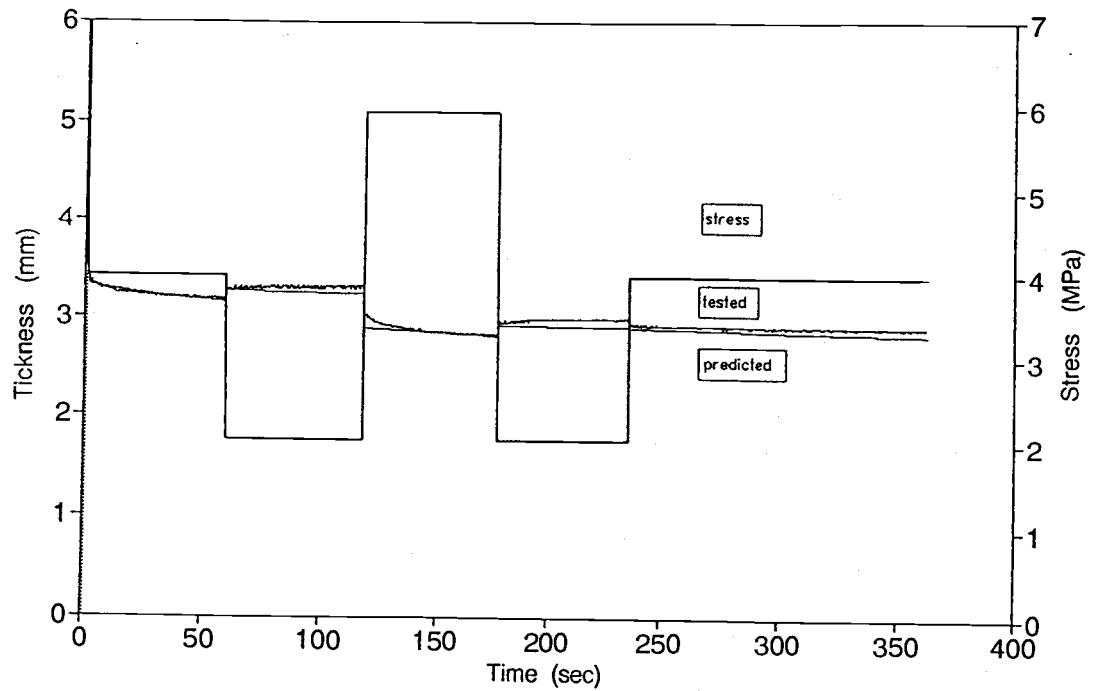
Figure 6.6. Comparisons between experimental and
predicted deformation for a specially
designed loading cycle.

6.3.1. Prediction of instantaneous behavior

From Figure 6.7. we can see that there are some differences between the predicted and experimental results. The discrepancy is within 7%.
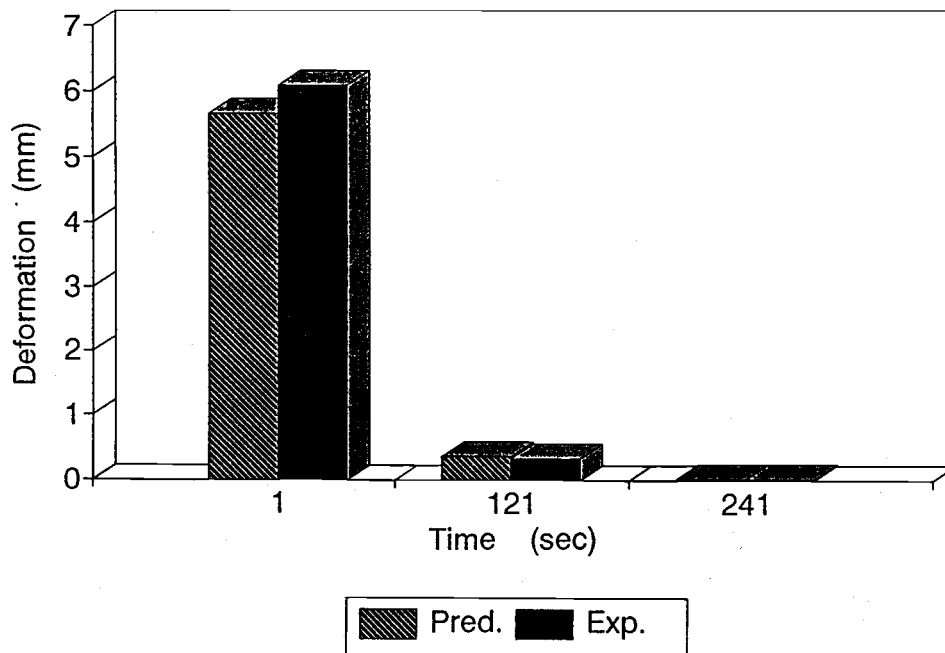
Figure 6.7. Comparisons of predicted and experimental instantaneous compression behavior (effect of EE1) for loading curve as Fig. 6.6 shown.

Figure 6.8 shows the difference between the results of instantaneous compression (at 121 sec) and relaxation (at 181 sec) under similar differential stresses. The deformation of compression (including effects of EPMF and EE1) obviously differs from that of relaxation (with only

effect of EE1). Therefore, the effects of EE1 can not represent the completed instantaneous deformation of compression conditions during wood composite manufacture. The EPMF is necessary to be developed to study this kind of behavior.
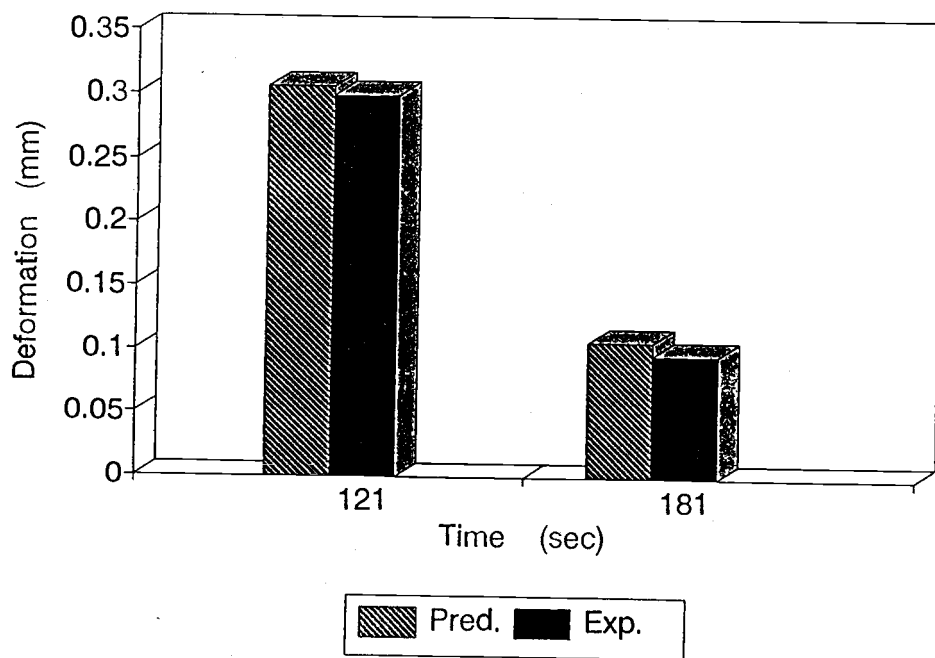
Figure 6.8. Comparisons between instantaneous relaxation deformation of EE1 and compression deformation of EPMF + EE1 for loading curve as Fig. 6.6. shown.

6.3.2. Prediction of time dependent behavior

Time dependent behavior mainly consists of the delayed elastic deformation and the viscous deformation which are

represented by EE2, EV2, and EV1. However, with the changes of structure (density), the rheological properties also vary.
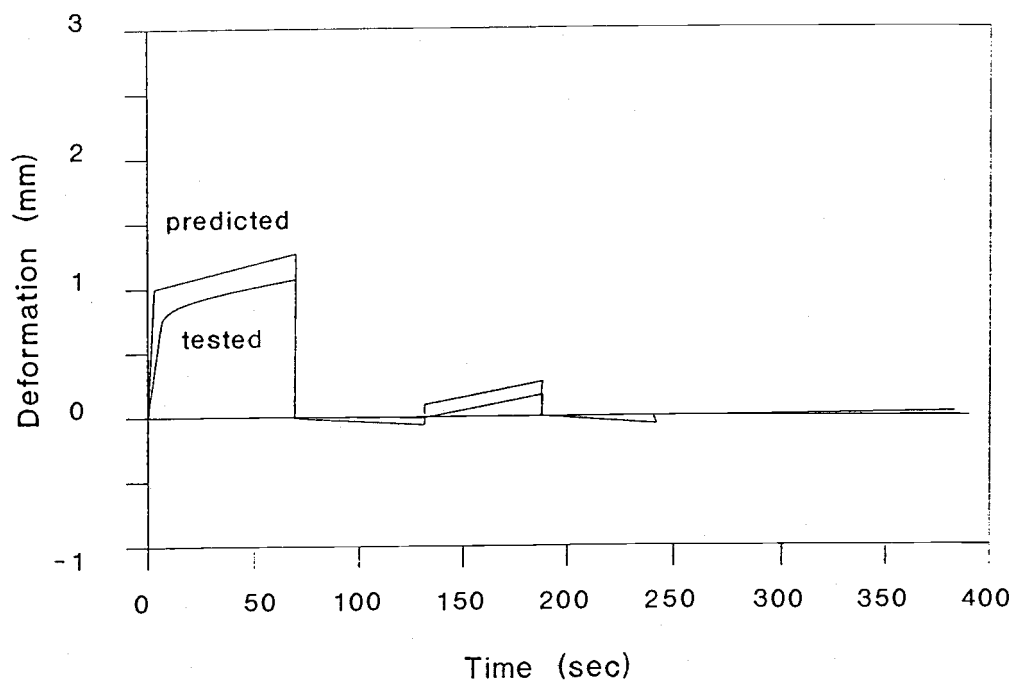
Figure 6.9. Predicted and tested time-dependent behaviors for the loading given in Fig. 6.6.

From Figure 6.9 we can see that the time dependent behavior was quite well predicted, especially at the later stages of deformation. The discrepancy in the early stages was less than 8%, and at the late stages was less than 5%.

6.3.3. The workable range of the model

The useful range of the loading pressure, density, temperature and moisture conditions is shown in Table 6.1.

Table 6.1. Approximate working ranges of the present model.

Compression pressure:	0 --	7 MPa
Density:	250 --	1200 kg / m^3
Temperature:	25 --	180 $^\circ$C
Moisture content:	0 --	16 %

6.3.4. Prediction of environmental effects

Temperature effects:

Figure 6.10 shows a typical example of predicted curves of rheological deformation that take place under a range of temperature conditions. Since the thermo-effects on properties of each element can be quantified and predicted, the thermo-effects on the rheological behavior of the whole material also can be predicted.
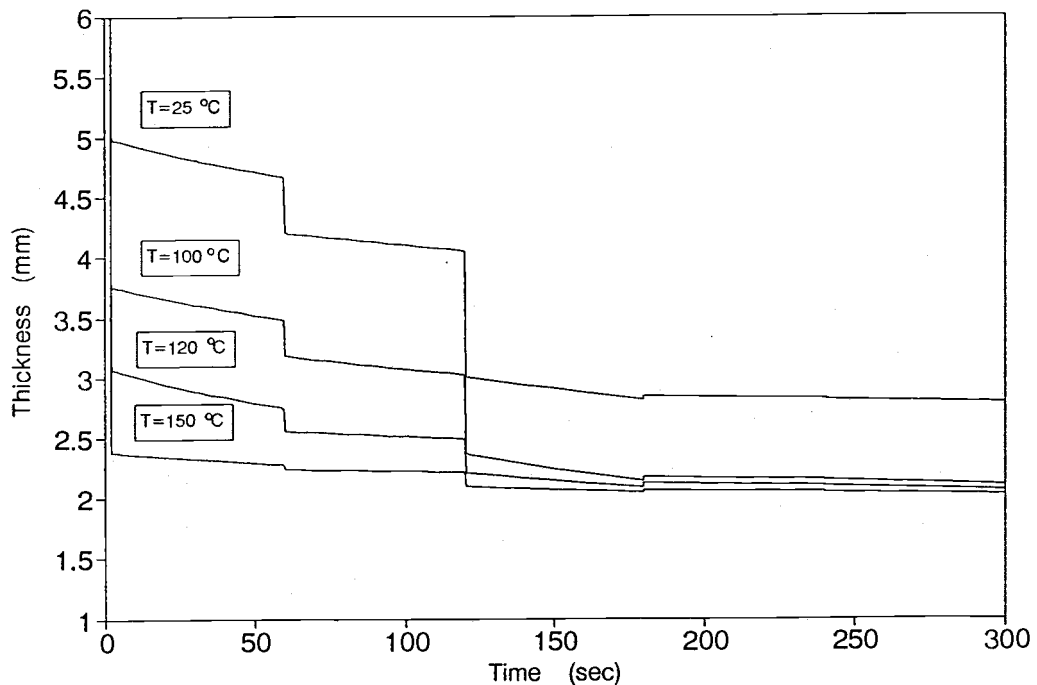
Figure 6.10. Predicted temperature effects on
rheological behavior for loading
curve shown in Fig. 6.6.
(MC = 16%, T = 25, 100, 120, 150°C).

Moisture effects:

Since the hygro effects on properties of each element

can be quantified and predicted, the hygro effects on the

rheological behavior also can be quantified and predicted.

Figure 6.11. shows examples of predicted curves for

deformation taking place under a range of moisture

conditions.
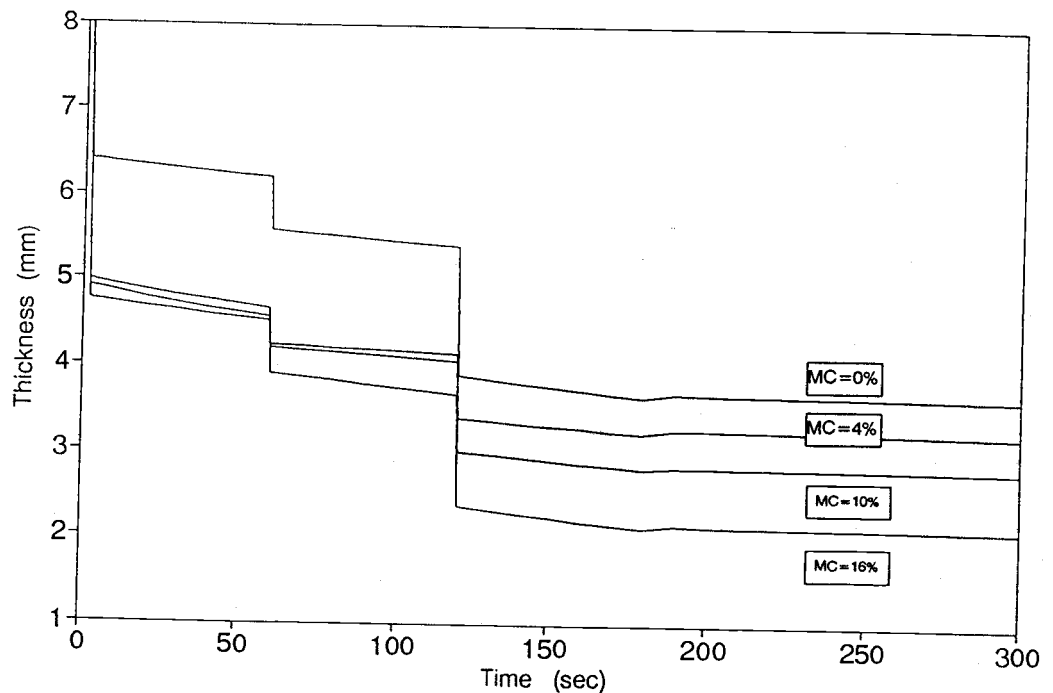
Figure 6.11. Examples of predicted moisture effects on
           rheological behavior for the loading
           curve shown in Fig. 6.6
           (T = 100 °C, MC = 0, 4, 10, 16 %).

6.3.5. Predicting initial thickness

The model may be applied in many ways to study the
materials behavior. For instance, if a specific density is
needed after compression, we can apply the model inversely
from the desired density (final thickness) to predict
initial thickness based on different compression cycles and
environmental conditions. Then we may design a loading cycle
and select initial thickness of specimen to produce required

thickness. Figure 6.12. shows an example of how to predict the initial thickness under a designed condition of loading, temperature and moisture (steady-state condition in this example) from known final thickness. Applying inversely calculation based on the model and test conditions, the initial thickness can be predicted (deformation start at right).
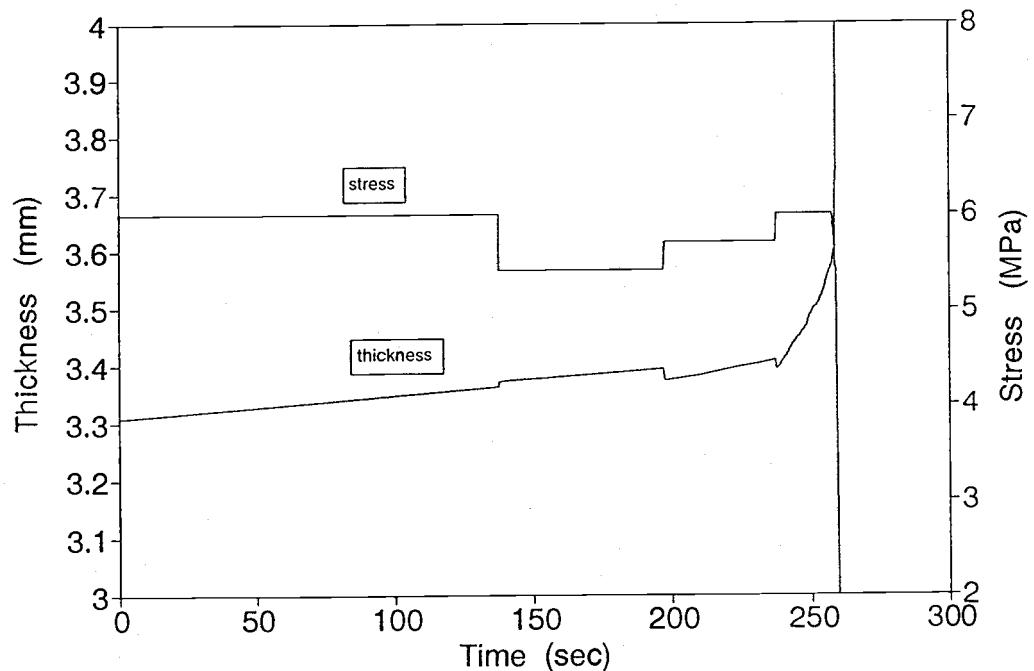
Figure. 6.12. Prediction of initial thickness from known required final thickness and pressing conditions (P = 6 MPa, T = 100 °C, MC = 0 %).

Due to the limited ranges of load, temperature and moisture investigated, the capability of this model has been verified only over a relatively narrow range.

The applicability of the model to other composite materials is not clear. However, having established the experimental and numerical approaches, it should be feasible to apply similar techniques to a diverse range of raw material combinations.

The present research has focused on experimental techniques. However, some brief discussion about thermo-hygro effects on the behavior will also be presented in the next chapter.

Some specific examples of material behavior that does not fall within the assumptions of the general rheological theories will also be considered.

CHAPTER 7. RESULTS AND DISCUSSION II

--Thermo-hygro rheological behavior--

Thermo-hygro-rheological behavior of wood furnish

materials (as functions of density, time, temperature and

moisture condition) during compression will be deliberated

in this chapter.

The underlying mechanisms which may influence

rheological characteristics are addressed in section 7.1,

then sections 7.2, 7.3 and 7.4 present the effects of the

structure, temperature and moisture respectively. The energy

consumption of the rheological deformation are addressed in

section 7.5.

7.1. Causes of the rheological behavior of wood furnish

    materials under compression

Clearly, the wood furnish materials are deformed and

partially damaged (micro-structurally) under the influence

of varying compressive pressures. The materials sustain

intricate elastic, delayed elastic, viscous, plastic-micro-

fracture changes, and these progress in an unsteady-state

fashion as pressing proceeds (Fig. 7.1). Therefore, the

behavior is the superposition of the five different

elemental behaviors.

Theoretically, the rheological behavior of the materials should be a superposition of the five elements' behavior and their interactions (although the later have not been included in the present models). After the rheological parameters of the tested materials have been obtained, the contribution of each element may then be predicted for a given loading cycle.
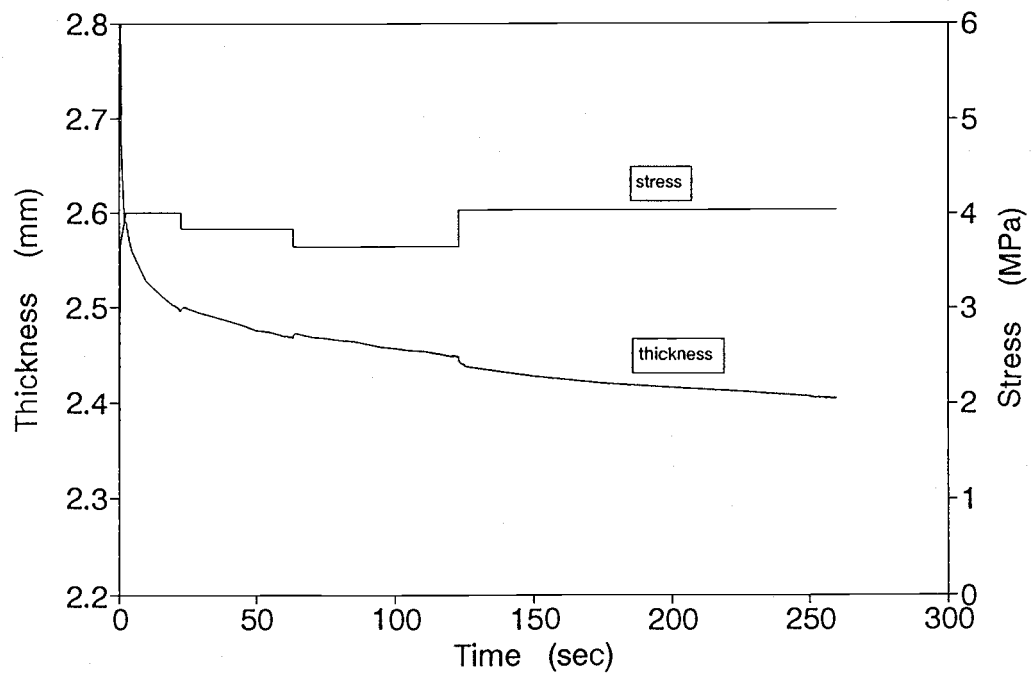
Figure 7.1. Curves representing typical rheological behavior of a fiber network under compression (T = 100 °C, MC = 10 %).

7.1.1. Predicted behavior of EE1 for a given loading
       cycle

Since E1 is affected by density, the actual deformation
of EE1 is caused not only by varied stress but also by
changes in structure.

The behavior of EE1 varies nonlinearly with density,
but the deformation of EE1 may be cumulatively predicted:

$$\varepsilon_{EE1} = \frac{\sigma}{E1} = \frac{(th-the1)}{th}$$

$$the1 = th(1-\frac{\sigma}{E1}) \hspace{3cm} (7.1)$$

where, th: given thickness.
        the1: EE1 effected thickness.

Deformation of EE1 = th - the1.

Applying this equation (7.1) to the experimental data
will enable the deformation of this element during a
specified test to be predicted. In this procedure, element
values (which continuously change with density) are obtained
from the measured thickness versus time data. Stress values
are those actually used in the corresponding compression
tests. This approach has been used for all the following
elements. Figure 7.2. shows the predicted behavior of EE1
under the given loading sequence.
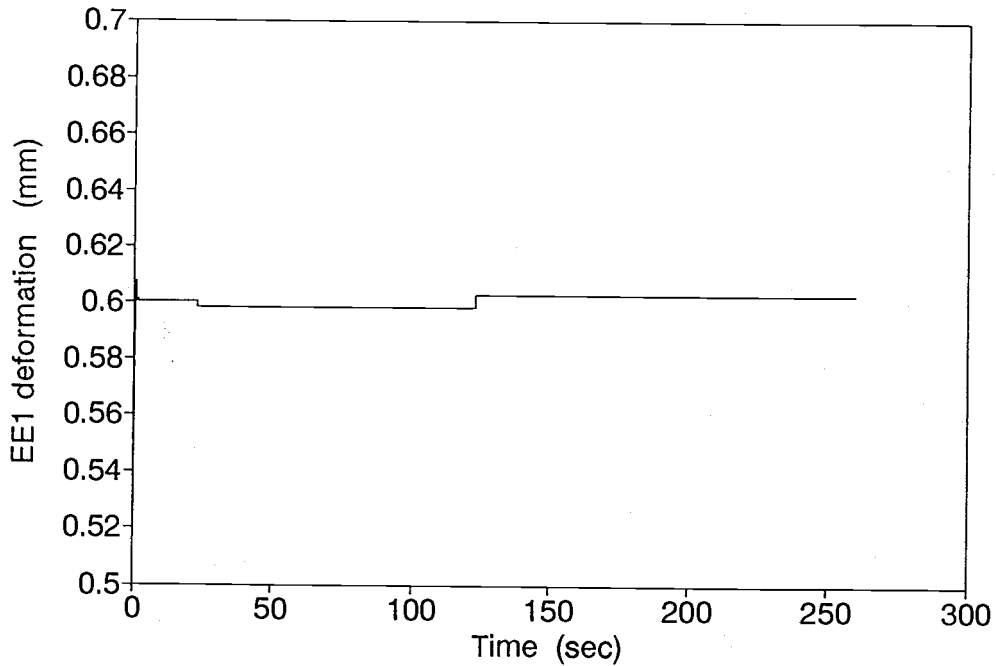
Figure 7.2. Predicted behavior of EE1 (derived from loading cycle of Fig. 7.1, T = 100 °C, MC = 10 %).

7.1.2. predicted behavior of EPMF for a given loading cycle

Deformation sustained by EPMF consists of the deformations from given stress and from consequential changes in density. Since the behavior of EPMF varies in a nonlinear fashion with density, a calculation of the deformation of EPMF during any given testing cycle may be predicted (Fig. 7.3).
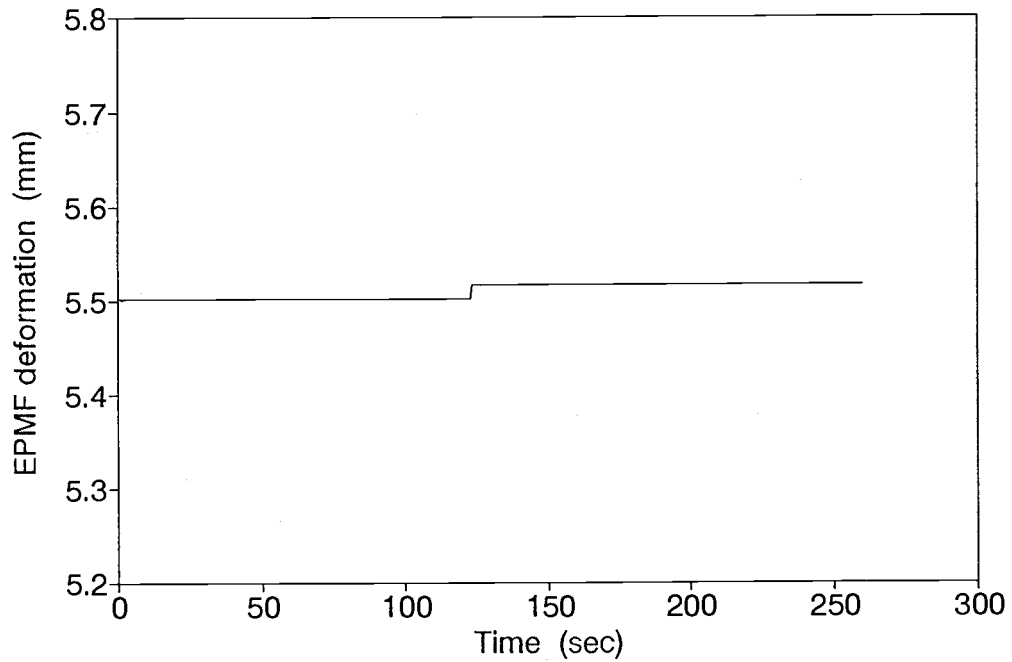
Figure 7.3. Predicted behavior of EPMF (derived from loading cycle of Fig. 7.1, T = 100 $^{\circ}$C, MC = 10 %).

$$\varepsilon_{PMF} = \frac{\sigma}{PMF} = \frac{(th-thpmf)}{th}$$

$$thpmf = th\left(1 - \frac{\sigma}{PMF}\right) \tag{7.2}$$

where, th: given thickness.
       thpmf: EPMF effected thickness.

Deformation of EPMF = th - thpmf.

7.1.3. Predicted behavior of EV1 for a given loading
    cycle

Following initial instantaneous deformation, the
material continuously deformed under constant compression.
This deformation mainly consists of delayed elastic
deformation from both EE2 and EV2, and the viscous
deformation of EV1. However, the values of E1 and PMF also
vary with the continuously changing density. This means that
the deformation of these two elements are also effected. The
deformation of this stage can be shown as the equation shown
at the start of chapter 5.

Since the behavior of EV1 is nonlinear and based on
density, a calculation of the deformation of EV1 at each
test may be conducted as follows.

$$\varepsilon_{EV1} = \frac{\sigma t}{K1} = \frac{(th - thv1)}{th}$$

$$thv1 = th\left(1 - \frac{\sigma t}{K1}\right) \qquad (7.3)$$

where, th: given thickness.
       thv1: EV1 affected thickness.
       t: time.

Deformation of EV1 = th - thv1.

Applying equation (7.3) to the experimental data
supplies the actual deformation from this element and how it
varies during the given testing cycle (Fig. 7.4). Since K1

is a function of density, any variation of load, which may

cause the variation of deformation, may affect the behavior

of EV1. Therefore, deformation of EV1 does not vary

continuously with the load.
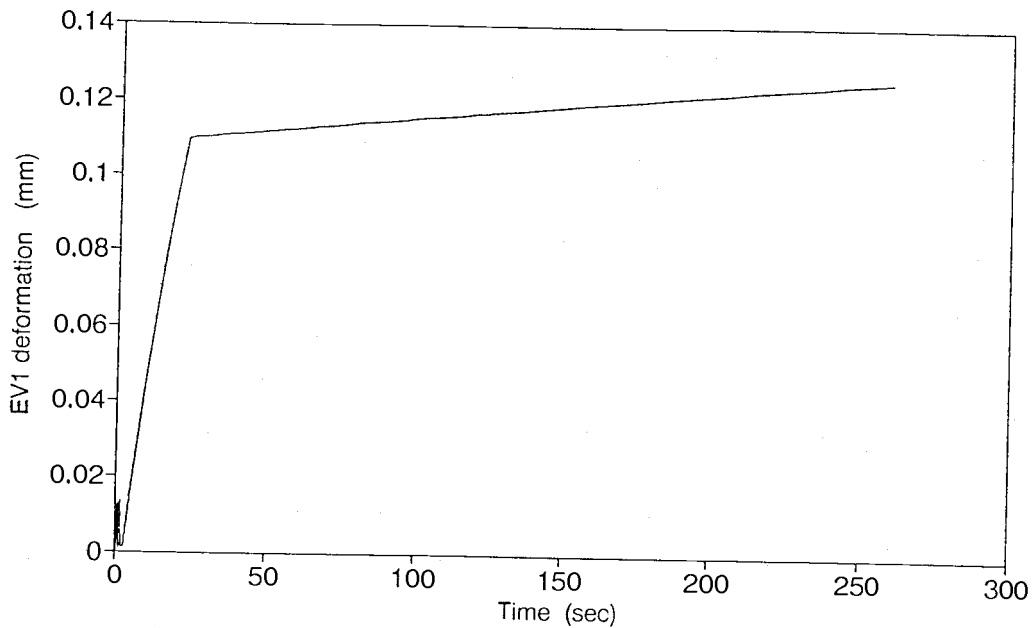
Figure 7.4. Predicted behavior of EV1 (derived from
loading cycle of Fig. 7.1, T = 100 °C,
MC = 10 %).

7.1.4. Predicted behavior of EE2 and EV2 for a given
loading cycle

The behavior of EE2 and EV2 (delayed elastic) is

represented by the following equation:

$$\varepsilon_{(delayed\ elastic)} = \frac{\sigma}{E2} - \frac{\sigma}{E2} e^{\frac{-E2\ t}{K2}}$$

(7.4)

Behavior of EE2:

The deformation of EE2 also is stress and density induced. It is the total deformation subtracted by the deformations of other elements.

It follows that:

$$\varepsilon_{EE2} = \frac{\sigma}{E2} = \frac{(th-the2)}{th}$$

$$the2 = th(1-\frac{\sigma}{E2})$$

(7.5)

where, th: given thickness.
       the2: EE2 effected thickness.

Deformation of EE2 = th - the2.

Again, deformation from this element may be predicted (Fig.7.5.).
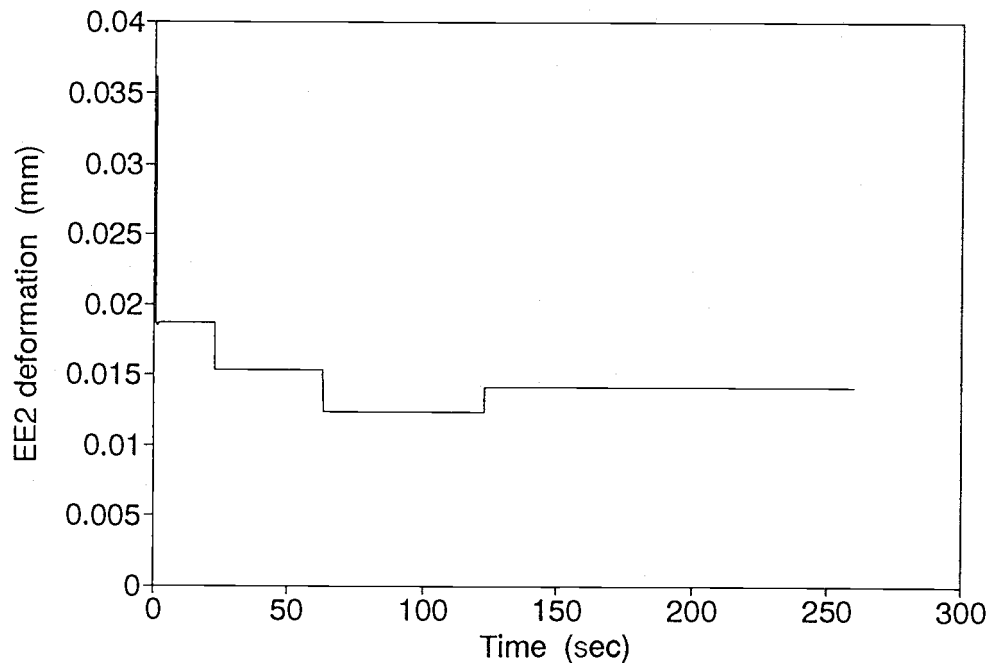
Figure 7.5. Predicted behavior of EE2 (derived from loading cycle of Fig. 7.1, T = 100 °C, MC = 10 %).

Behavior of EV2:

The actual deformation of EE2 associates to the properties of EV2. The values of EE2/EV2 (see equation 7.6) is given by the strains of EE1, EPMF, EV1 and EE2 subtracted from the total strain.

$$\varepsilon_{EE2/EV2} = \varepsilon_{total} - \varepsilon_{EE1} - \varepsilon_{PMF} - \varepsilon_{EV1} - \varepsilon_{EE2}$$

$$\varepsilon_{EE2/EV2} = \frac{\sigma}{E2} e^{\left(\frac{-E2t}{K2}\right)} \tag{7.6}$$

$$the2v2 = th\left(1 - \frac{\sigma}{E2} e^{\left(\frac{-E2t}{K2}\right)}\right) \tag{7.7}$$

where: th: given thickness.
the2v2: EE2 and EV2 affected thickness.
t: time.

Deformation of EE2/EV2 = th − the2v2.

The strain of EV2 may be reconstructed individually or in the form of EE2/EV2 (equation 7.6) for each test.

As for the other elements, applying this equation (7.7) to the experimental data enables the actual deformation from this element and how it varies to be predicted (Fig. 7.6).

It should be remembered that EE2 and EV2 both change continuously with changing density. The impact of this is most obvious when loads change instantaneously. Then, density and corresponding element values change greatly and this results in apparent instantaneous delayed elastic deformation. This is clearly contrary to expected behavior

associated with the acknowledged effect of density on elemental properties. The superposition of the behavior of these two elements will show the delayed elastic behavior (Fig. 7.8).
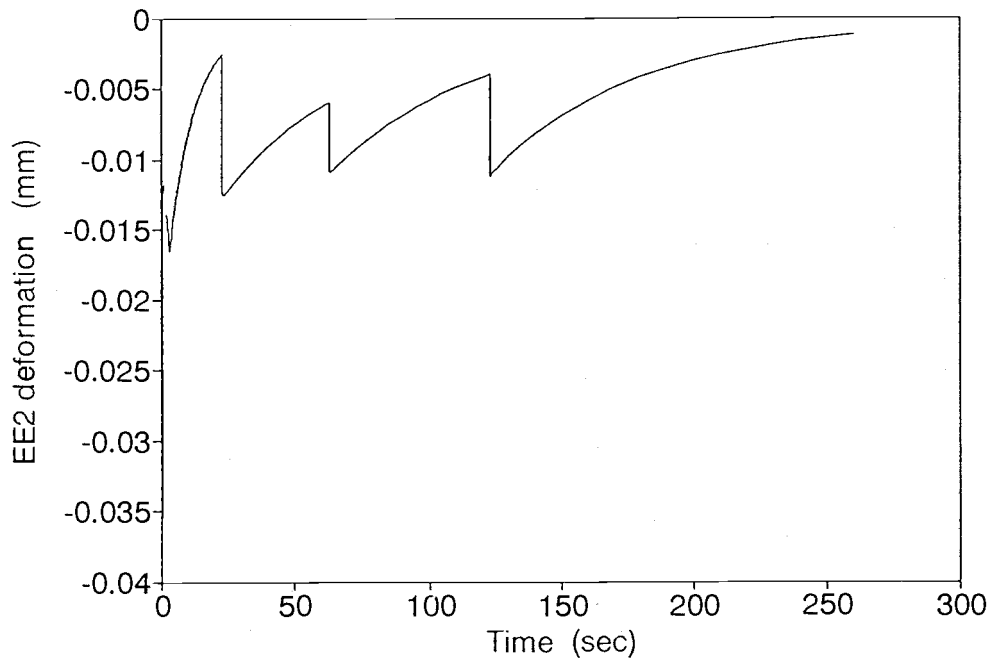
Figure 7.6. Predicted behavior of EE2/EV2 (derived from loading cycle of Fig. 7.1, T = 100 °C, MC = 10 %).

7.1.5. Predicted behavior of all five elements combined

Figure 7.7 shows a curve reconstructed from the behavior of the five elements as discussed above. Figure 7.8 shows the deformations of five elements at each stage of compression after instantaneous deformation. It may help us to understand the rheological behavior of each element.
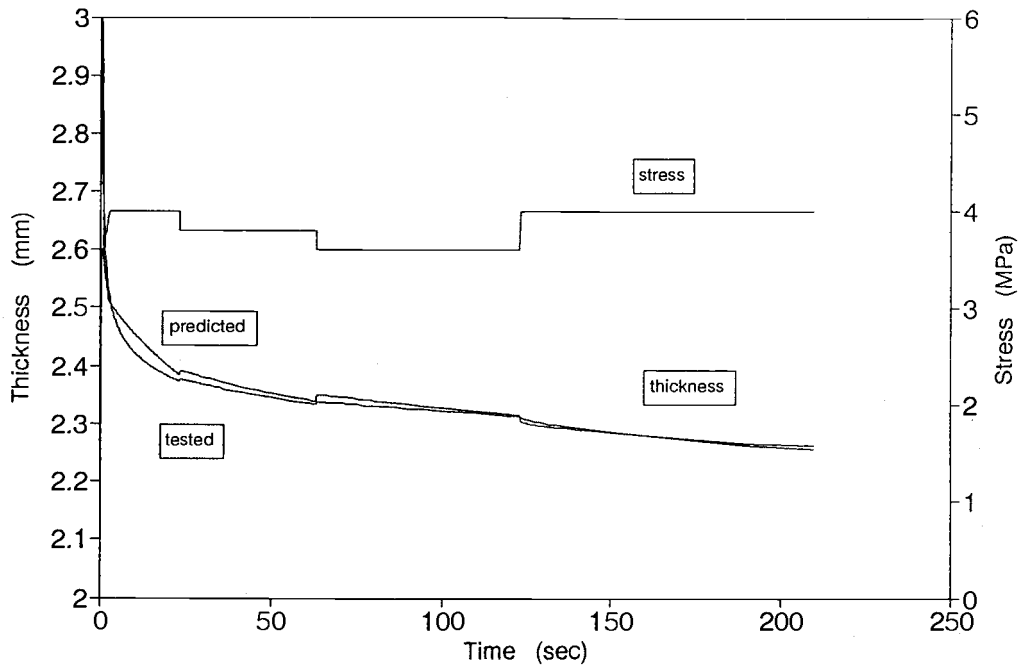
Figure 7.7. A reconstructed rheological curve from the behaviors of the five elements (combination of Fig.7.1, 7.2, 7.3, 7.4, 7.5, 7.6).

The deformation in the initial stage of compression mainly is from the effects of EPMF and EE1 which reflects the relocation and fracture of the fibers (EPMF, Fig.7.3), and elastic effects (EE1, Fig. 7.2). With time increases, the deformation continuously increases even during periods of constant compression. One part of this increase is from the delayed elastic effect; the effect of EE2/EV2 rapidly increases from negative values to zero (EE2/EV2, Fig. 7.6 and 7.8) so that the deformation of the EE2 is delayed (EE2, Fig. 7.5 and 7.8). However, this delay also depends on the variation of density. Another part of the time-dependent deformation is due to viscous deformation (EV1 in Fig. 7.4

deformation is due to viscous deformation (EV1 in Fig. 7.4
and 7.8). Deformations of these three elements continuously
varied with time (Fig. 7.1. and 7.8).
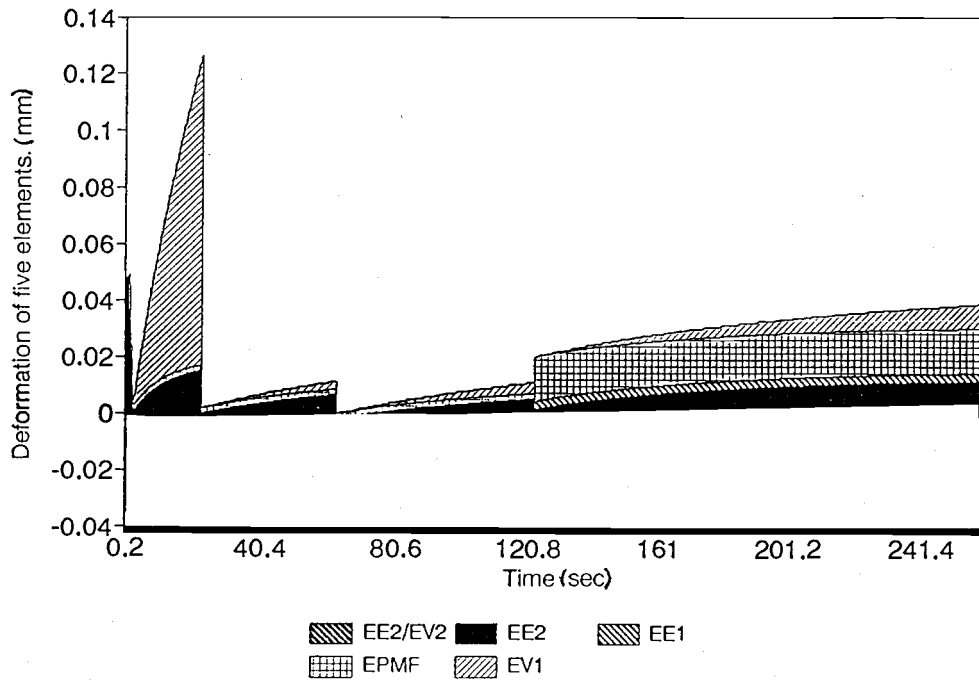
Figure. 7.8. Five-element deformation after initial
instantaneous deformation (combination of
Fig. 7.2, Fig. 7.3, Fig. 7.4, Fig. 7.5,
Fig. 7.6).

With density increases, the effects of EPMF and EE1
also vary. This suggests that with increasing density,
fracture and relocation of the micro-structure also takes
place. High density could possibly lead to more uniform
internal stress distributions.

After a certain time period, the delayed elastic
deformation is fully developed and subsequent deformation
rates are approximately linear (when values of EE2/EV2

strain mainly is from EV1 (the viscous properties of the fiber network, and the effects of EE1, PMF, and EE2/EV2 on the materials varied insignificantly).

If the behavior of the five elements could be controlled in a desired way, the hot pressing process and the quality of final products may be improved. For instance, in order to avoid any destruction of wood-adhesive adhesion, the adhesive should not be fully polymerized until the deformation (behavior) of EE1 and EPMF are fully developed.

Since the property of EE1 increases with density, under similar stress conditions, the higher E1 value leads to lower strains and that results in reduced spring back (thickness increase). Therefore, EE1 may be manipulated to avoid internal failure during hot press opening. The localized internal bond strength should be larger than the internal stress upon press opening to avert EE1 product failure.

The dimensional stability of wood composite materials at later stage of hot pressing (even after pressing) mainly depends on the behavior of EV1, EE2 and EV2 from Fig. 7.8. The larger the values of these elements, the less time-dependent deformation (relaxation process) will occur. Therefore, the better dimensional stability.

This research therefore, is important for its potential application in product manufacture (hot pressing).

7.2. Structural effects

A study of the rheological behavior in terms of structural properties is important, especially for engineering composite materials. The structure and associated properties change continuously as pressing proceeds (see Fig. 7.9) and it directly effects the manufacturing process and the properties of the final product.
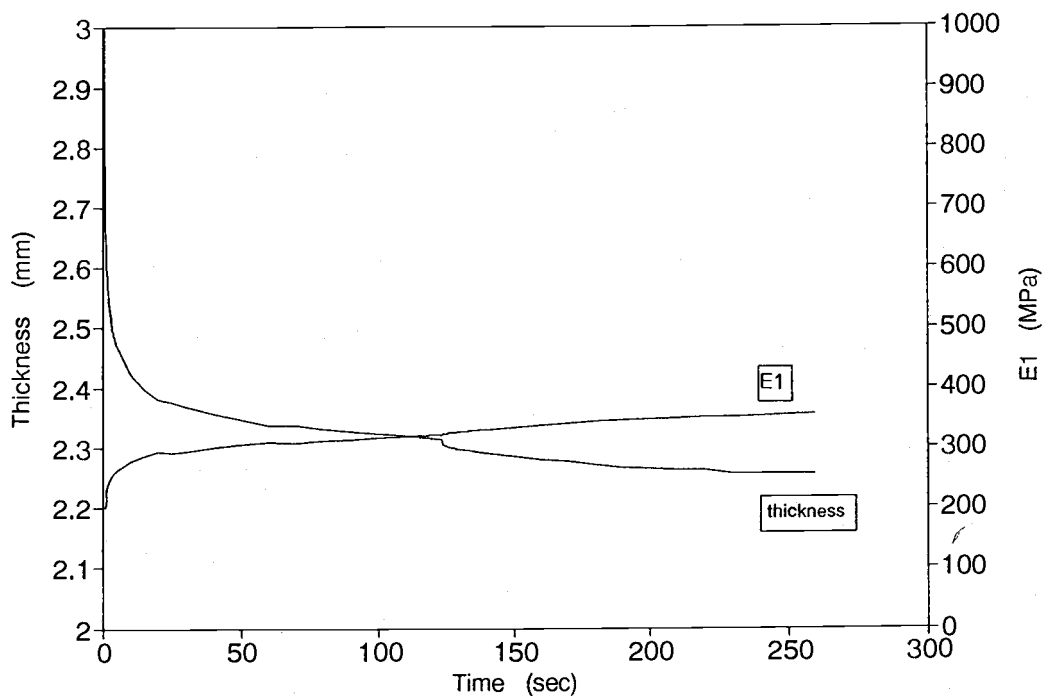
Figure 7.9. An example E1 curve varies with specimen thickness change during the test.

Generally, the rheological behavior of materials is described as a function of stress, strain or rate of strain. However, in the consideration of wood-based composites hot pressing, the structure (for instance, the micro-structure distribution, fiber orientation, density profile, raw materials properties, and the wood-adhesive system) which directly influences total mechanical properties becomes an extremely important factor.

The rheological behavior of materials during compression dependents on the effects of structure (as we have already discussed at chapter 3), as well as on time. When the materials are densified, they form a lot of open or closed voids, varying in shape and size. Voids within the system are formed due to extraction or volatilization products of chemical reactions of adhesive solvents, moisture adsorbed by the adhesive and wood material, the porous nature of wood, and "defects" due to unsuccessful formation processes. The effective surface areas within materials vary and these are linked to internal stress distributions. At lower densities, the voids are large and the effective surface area is low. The effective stress (which only acts on the non-porous part of the system) therefore is concentrated on the effective surface area and it may approach that at high density condition. At high density conditions, the voids are reduced and the mean effective surface (contact) is increased, and the effective

stress therefore, may be relatively low. Consequently, with the densification process, material properties continuously change, and the contribution of each element behavior also varied (Fig. 7.10).
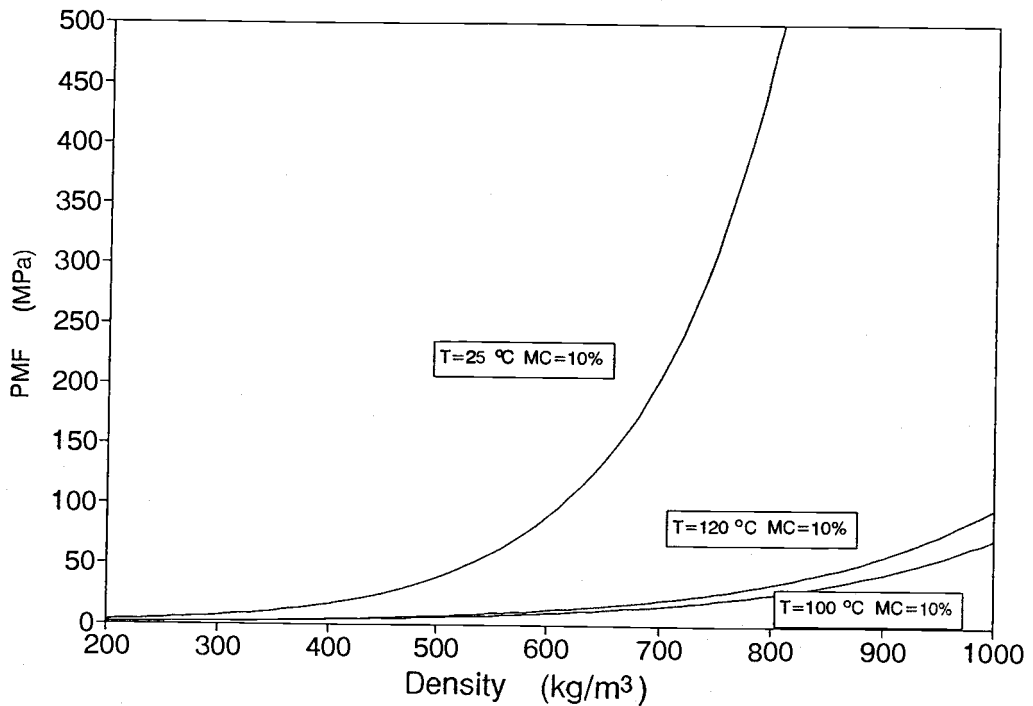
Figure 7.10. EPMF element properties at three different conditions of temperature and moisture content.

7.3. Temperature effects

The effects of temperature on the rheological behavior appear to be significant, especially in the initial stages of compression. The higher the temperature, the larger the initial deformation. This is demonstrated in Figure 7.11,

which shows thermo-rheological behavior during steady-state compression for a range of temperatures (in this case, all at 10% moisture content and similar compression conditions).

To determine the magnitudes of the thermal effects, it is necessary to determine the thermal effects on each element properties and their behavior. Thermo-effects on the composites are directly related with the thermo-effects on each element's property. Figures 7.12 to 7.16 show the thermo-effects on element properties. More information about the thermo-effects on rheological properties of materials may be found in Appendix II.
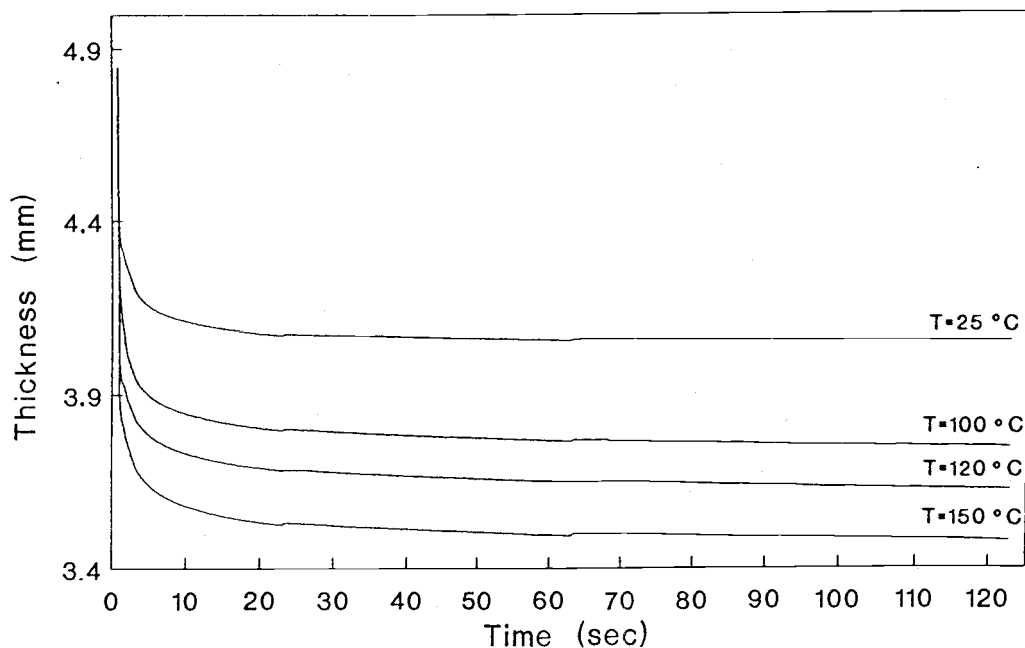
Figure.7.11. Temperature effects on fiber network deformation (MC = 4 %).
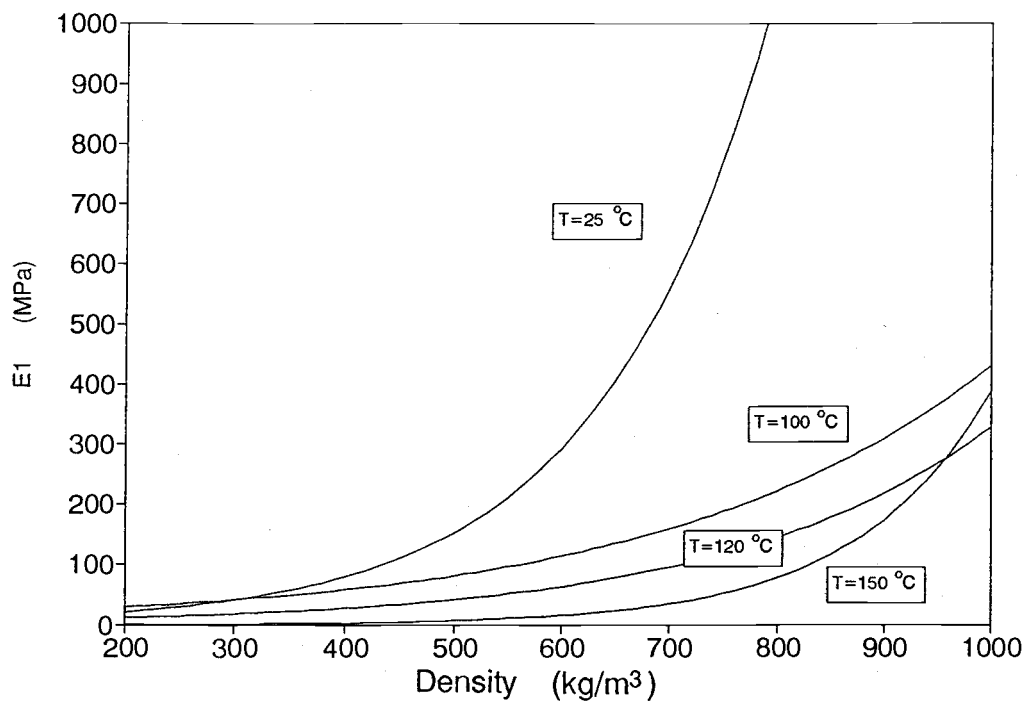
Figure 7.12. The effects of temperature on E1
(at MC = 10) %
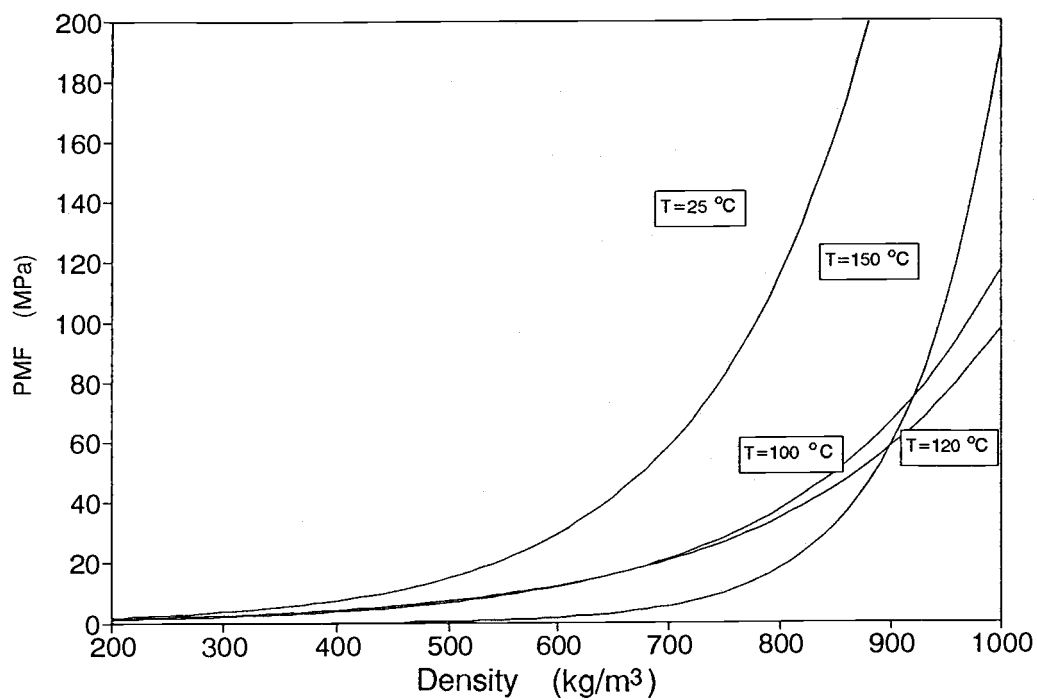
Figure 7.13. The effects of temperature on PMF
(at MC = 10 %).
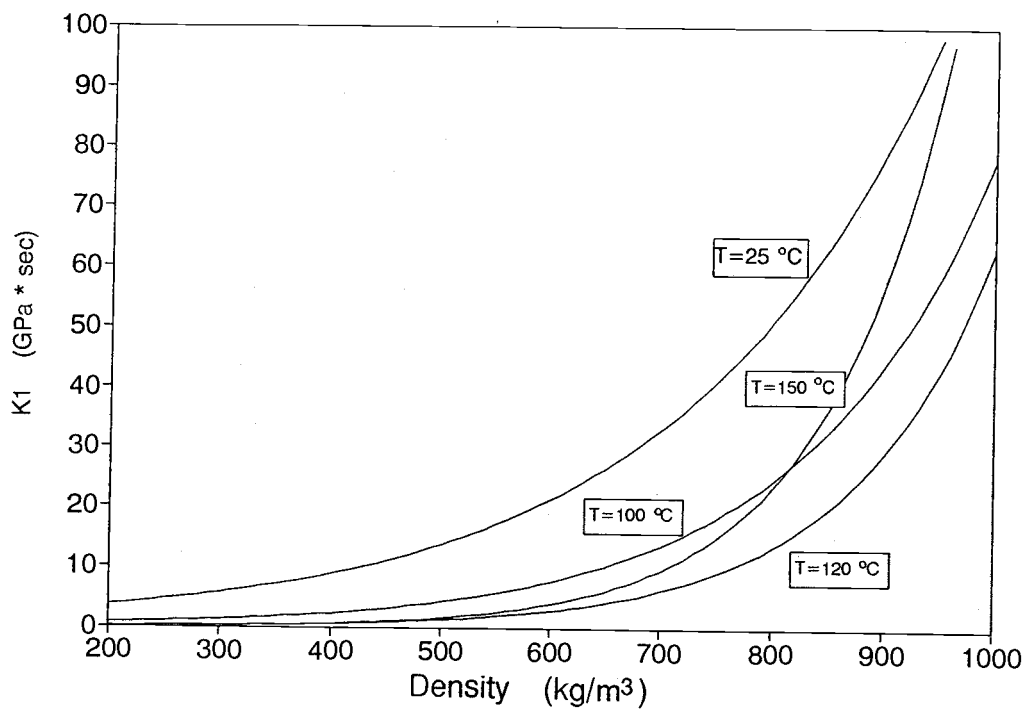
Figure 7.14. The effects of temperature on K1
(at MC = 10 %).
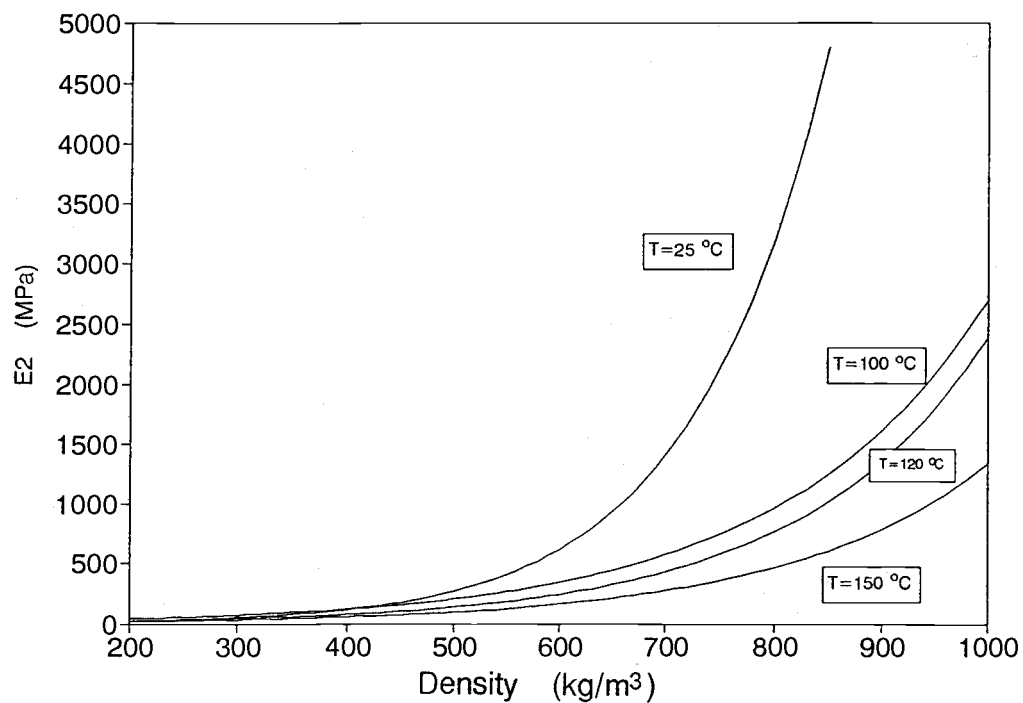
Figure 7.15. The effects of temperature on E2
(at MC = 10 %).
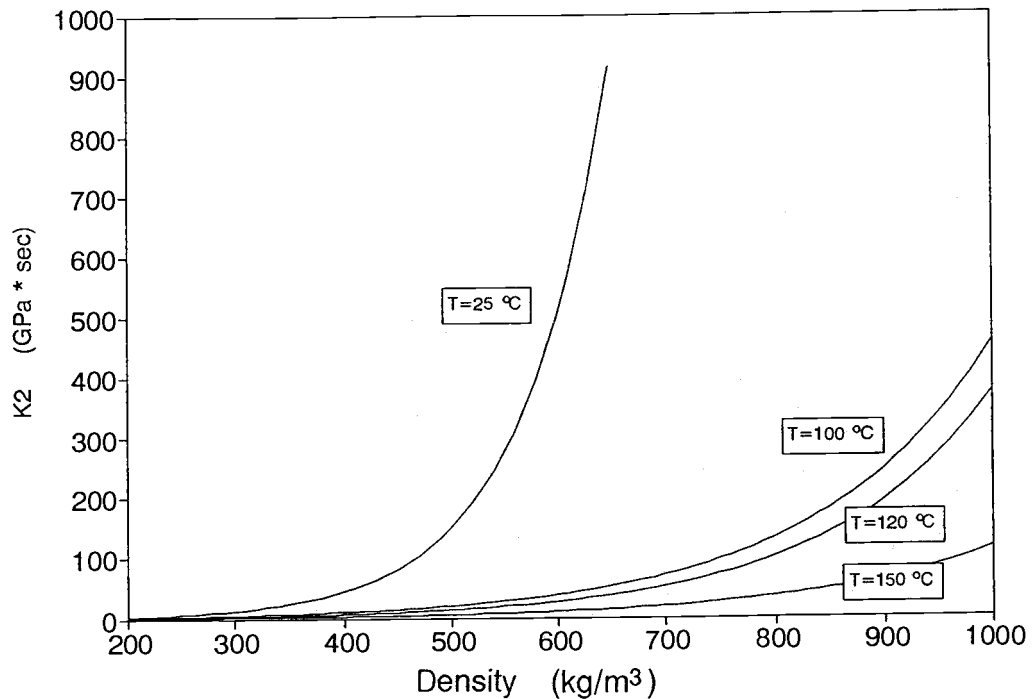
Figure 7.16. The effects of temperature on K2
(at MC = 10 %).

Under different temperature conditions, the rheological

properties of materials vary with density in different

fashions. Within most test ranges, higher temperatures cause

lower element property values, that means the more thermo-

effects on deformation of the materials.

Clearly, this information suggests that the thermal

effects of rheological properties of materials can be

quantified.

It is interesting to see some significant difference of thermo-effects on the materials at 150 $^{\circ}$C. The elements' properties first vary predictably (as at other lower temperatures) with density until about 700 kg/m^3. The deformation of the material then, increase significantly so that the values of element properties at 150 $^{\circ}$C disproportional higher than at under lower temperatures (such as 100 and 120 $^{\circ}$C). This information may help us to produce dimensional stabilized products. The relationship between this phenomena and hygro-effects on the rheological behavior will be discussed in the next section.

7.4. Moisture effects

The effect of moisture on the rheological behavior of fiber network is also significant. Figure 7.17 shows the hygro-rheological behavior during consolidation at a range of moisture conditions (0, 4, 10, 16%), a constant temperature (150 $^{\circ}$C) and similar mean compression conditions (4 MPa). As expected, we can see that increasing moisture content results in greater rheological deformation (Fig. 7.17).

Figure 7.18 to 7.22 show the hygro-effects on the element properties.
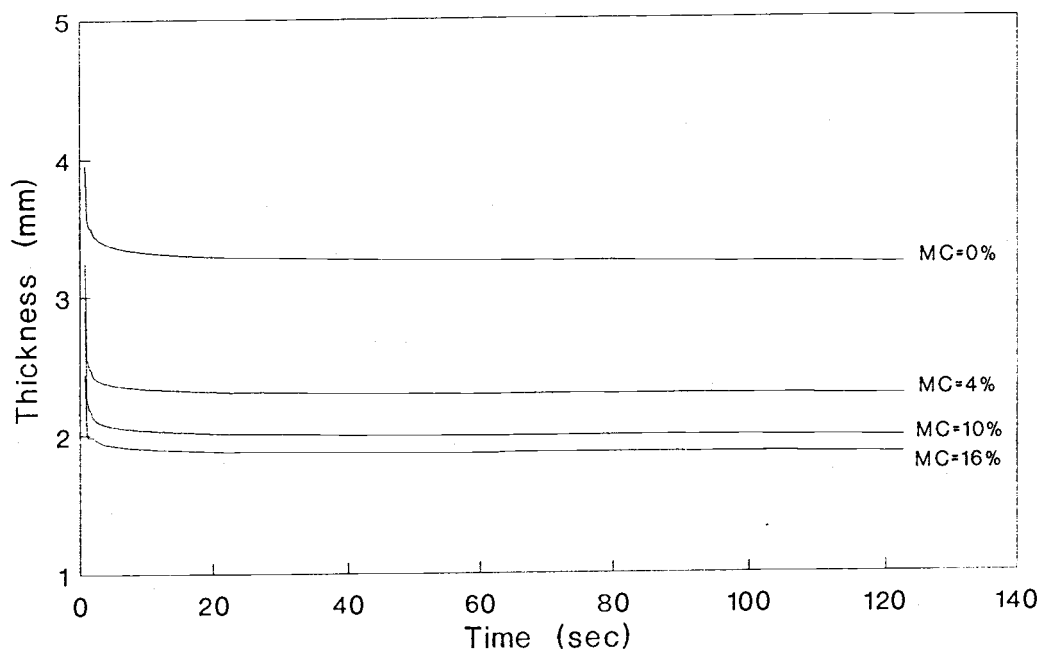
Figure 7.17. Moisture effects on overall deformation
(T = 150 ^{o}C, P = 4 MPa)
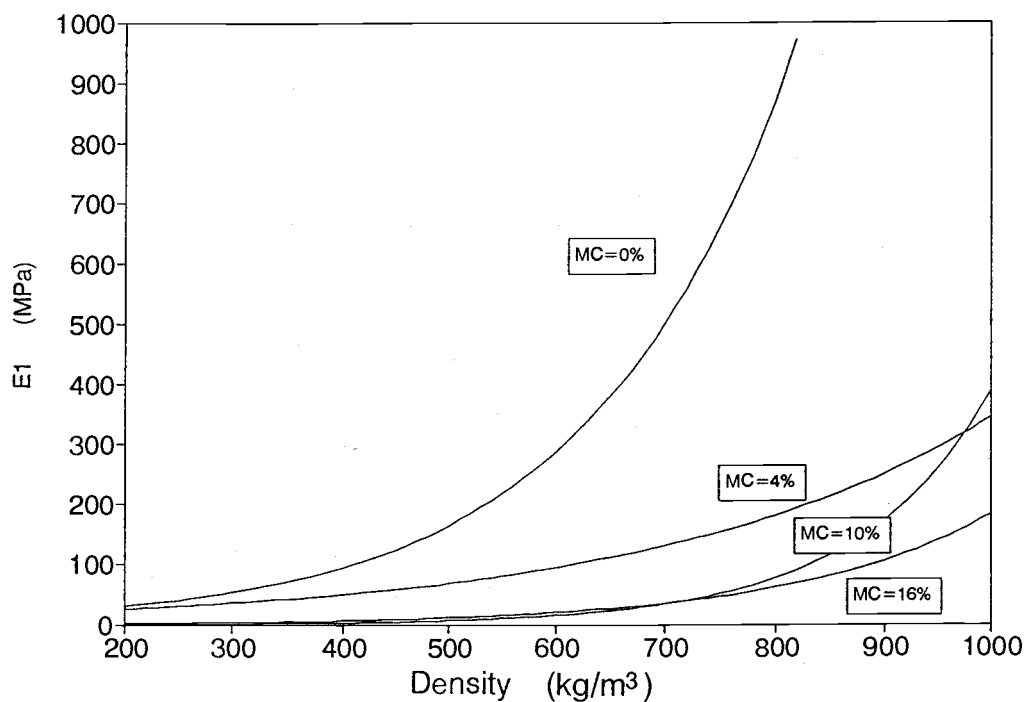
Figure 7.18. The effects of moisture conditions
on E1 (at T = 150 ^{o}C).
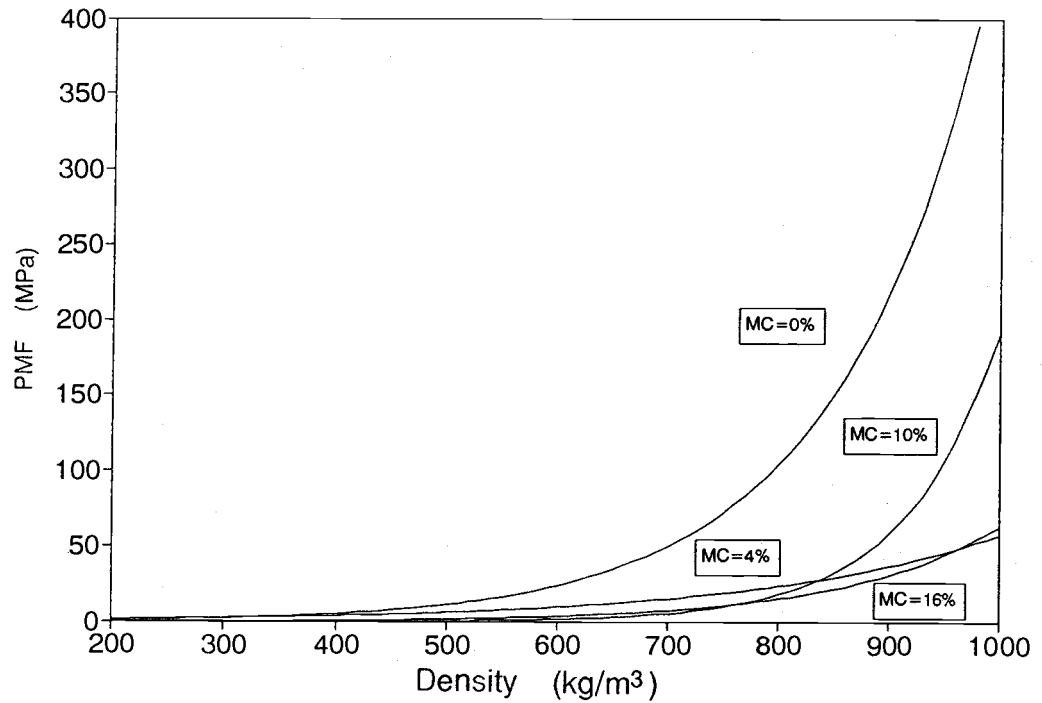
Figure 7.19. The effects of moisture conditions
on PMF (at T = 150 ^{o}C).
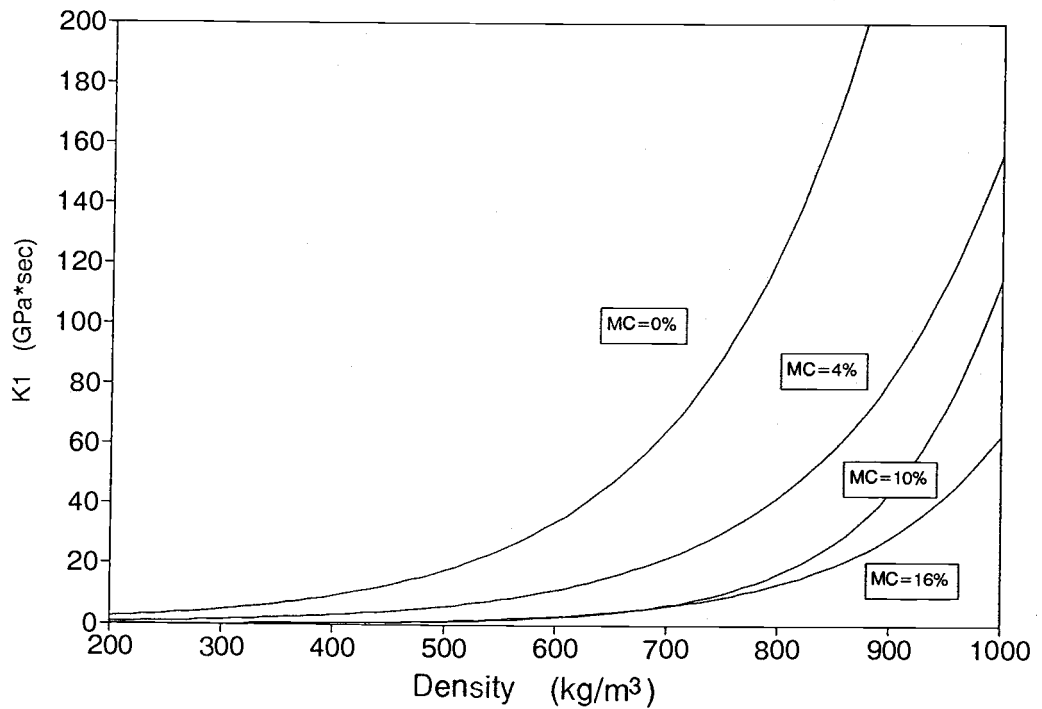
Figure 7.20. The effects of moisture conditions
on K1 (at T = 150 ^{o}C).
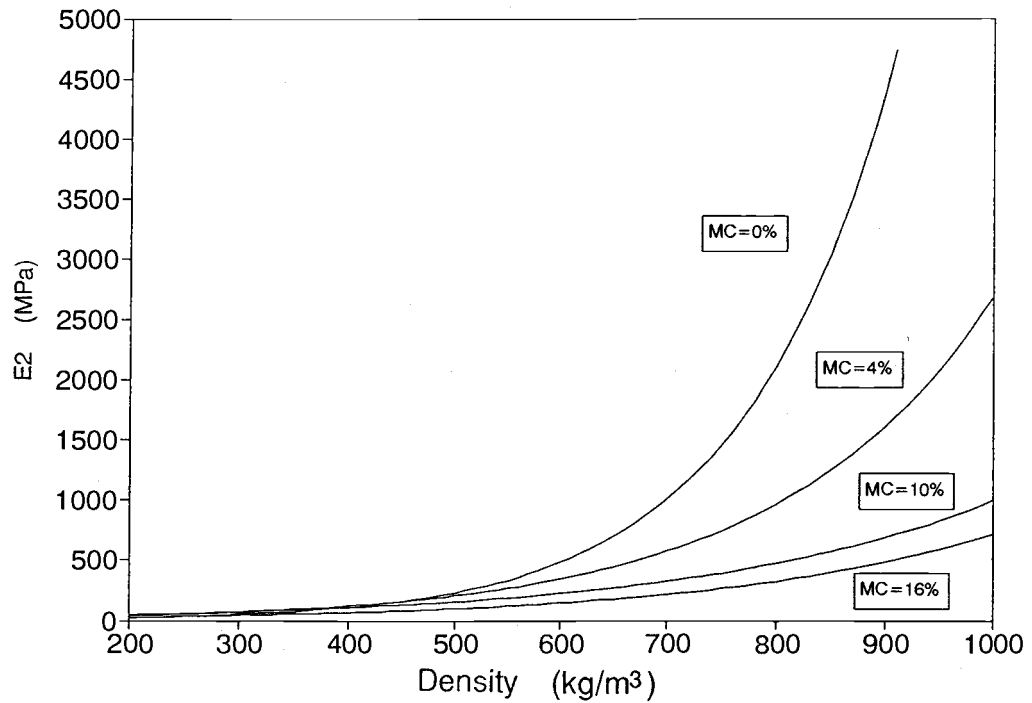
Figure 7.21. The effects of moisture conditions on E2 (at T = 150 $^{\circ}$C).
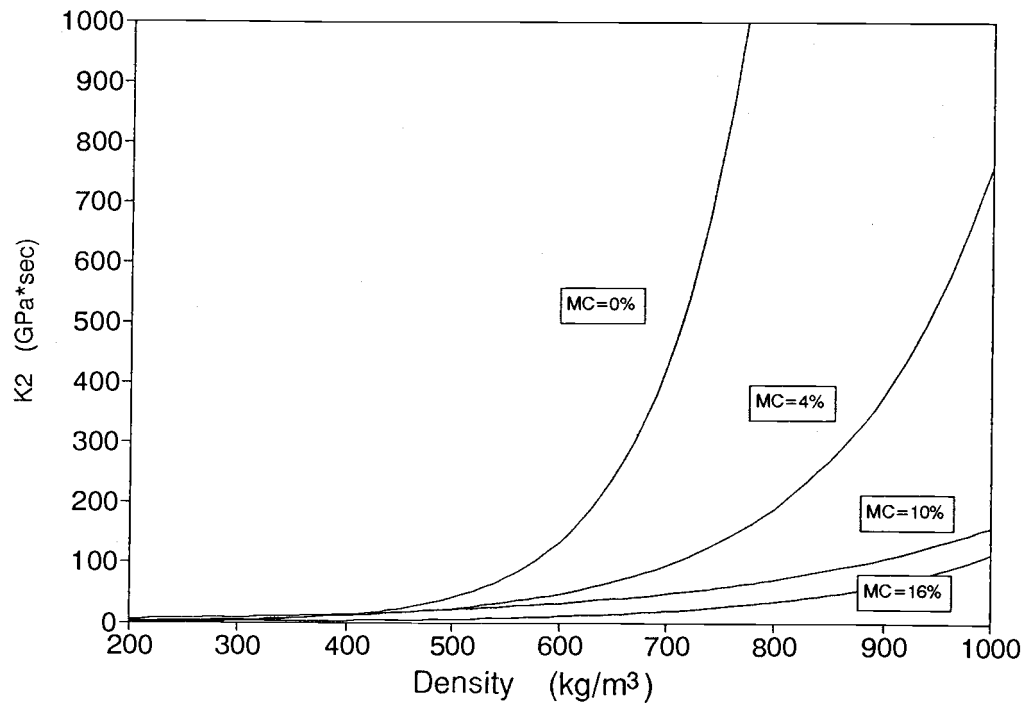
Figure 7.22. The effects of moisture conditions on K2 (at T = 150°C).

properties of materials. This information may help us to
produce high quality and dimensional stable products and may
stimulate further research in this direction.

7.5. Energy consumption of rheological behavior.

It is interesting to see that the energy associated
with deformation may be calculated as compression
progresses. This may be done for the whole material and also
for each element separately. Such an approach may provide
useful insights into the relative importance of each of the
mechanisms involved and may also provide a means for
reducing energy consumption (mechanical) in manufacture.

Figure 7.23 indicates that the energy (force *
deformation) consumed during compression results mainly from
EE1 and EPMF at the initial stages of compression. After
initial instantaneous deformation, the EV1 element is the
major energy consumer during the subsequent stage of
compression, and EV1 also continuously consumes a certain
amount of energy during later stages of the process.
However, EE2/EV2 together are definitely an important factor
which should be considered to reduce energy consumption in
hot pressing and the time dependent characteristics of the
materials. On the other hand, since the energy which is
stored by EE2/EV2 together can not be immediately released
when the hot press is opened, the stability of the final

products may be effected by this factor. It seems reasonable to reduce the energy of EE2/EV2 as a small value as possible. Since after initial stage, the Force varies relative small, the quantity of deformation of each element may be used to indicate the energy consumption.
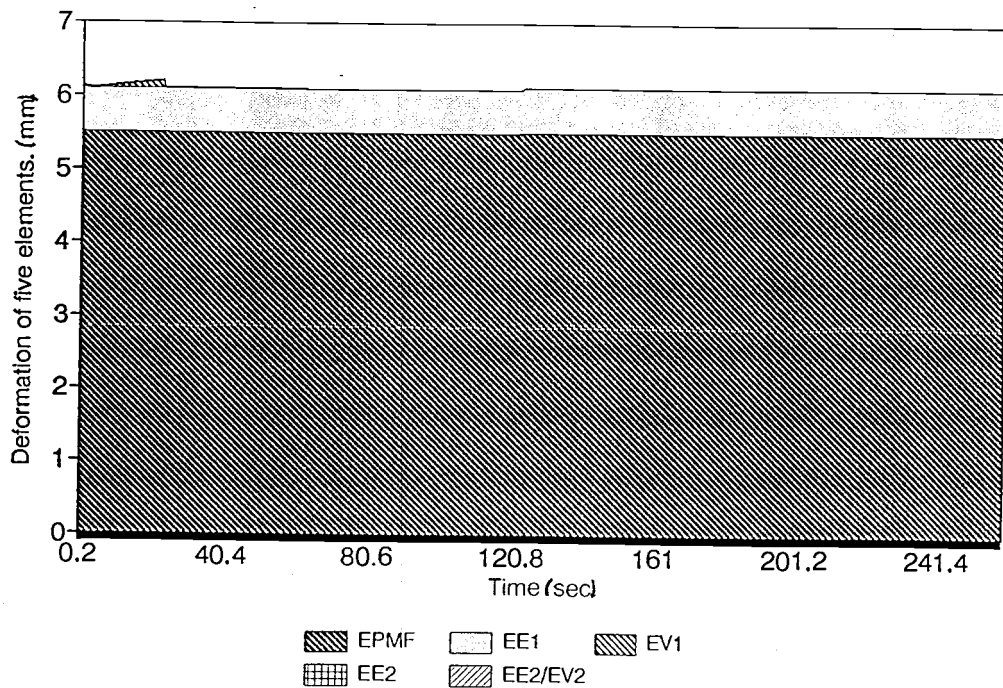
Figure 7.23. Energy (force * distance) consumption during typical of rheological deformation of the material.

From the above, it appears that a viable method to reduce energy during hot pressing is to achieve the final density distribution early in the pressing cycle, and then try to prevent the deformation of EE2, EV1 and EV2. Since after initial compression, the density has already achieved

relatively high values, the deformation of other elements can be manipulated by relative small external changes in stress. However, large increases making stage may increase the number and magnitude of deformation may cause the micro-fractures and this which may effect final products properties. Furthermore, to achieve final thickness too fast may induce some extra variation of density profile (which is developed with time) and that also effects the final products' performance.

This discussion presents preliminary results of this research. There are still many questions remaining. However, this research may stimulate further development of the rheological mechanics during hot pressing, both from theoretical and experimental standpoints.

CHAPTER 8.   CONCLUSIONS AND POSSIBLE FUTURE RESEARCH

8.1. Conclusions of current research

The following are the principal conclusions of the
current work:

1. Techniques and equipment have been developed to
investigate the rheological phenomena that occur during the
compression of wood fiber networks.

2. A five-element rheological model has been
established offering a means for investigating and
ultimately predicting the rheological behavior that occurs
during industrial hot pressing.

3. Experimentally quantifying rheological properties of
wood composite furnish materials has been developed.

4. Thermo-hygro effects on the rheological behavior of
wood composite materials have been investigated at moisture
contents from 0 to 16%, temperatures from 25 to 150 $^{\circ}$C and
stress ranging between 0 and 6 MPa.

5. Elastic-viscous-plastic-micro-fracture deformation
has been defined and quantified.

8. Elemental behaviors have been quantitatively studied
individually.

The research described here was designed to provide an
experimental and quantitative understanding of the

rheological behavior and the combined effects of temperature and moisture content. Ultimately it is expected that such techniques will give us more flexibility to select suitable component materials, and to design hot pressing processes to achieve required structures and properties of final products. If we can control the behavior of each of the component materials (to make them deform in a predictable fashion), we may efficiently produce high quality products from wood materials.

8.2. Possible future research

1. If more investigation could be done over a larger range of conditions, the rheological behavior of wood and wood composite materials, and their effects on other physical aspects may then be quantitatively understood.

2. The results of this study will ultimately be combined with those from parallel studies of: 1) heat and moisture transfer and 2) adhesion kinetics, so that the interaction of physical mechanisms operative during hot pressing may be understood quantitatively.

3. The application and improvement of the techniques we developed for this research may lead to further research to improve industrial products and manufacturing processes.

4. Micro-structural analysis may enable the rheological characteristics of materials to be linked to the materials' structure.

5. The behavior of adhesives and interfaces during hot pressing also should be investigated so that the complete wood-adhesive system can be better understood.

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APPENDICES

APPENDIX I

Computer programs for operating test system

and quantifying rheological properties of materials.

There are five computer programs in this appendix:

```
DECLARE SUB genctda (alldat!, load!)

10
'    WOOD COMPOSITES HOT PRESSING SIMULATION TEST PROGRAM
'    1989-7-26 BY SHAN REN FOR Ph.D THESIS.
CLS
LOCATE 10, 10, 1, 1
PRINT "WLCOME TO THE COMPOSITES MANUFACTURING SIMULATION TEST SYSTEM"
LOCATE 15, 28
PRINT "PART III  TEST"
100  IF INKEY$ = "" THEN GOTO 100

PRINT "    The functions of this program are:"
PRINT "    1. Composites manufacturing multi-simulation test:"
PRINT "        a. dynamic and static test on materials stress and strain,"
PRINT "        b. steady state condition test,"
PRINT "        c. unsteady state condition test,"
PRINT "        d. hygrothermo-effects,"
PRINT "        e. heat and moisture transfer measure and control,"
PRINT "        f. vapor condition,"
PRINT "    2. Experimental equipments control:"
PRINT "        a. minature insulated pressing system,"
PRINT "        b. data collection and conversion system, "
PRINT "    3. Enhancing and Controlling MTS test function:"
PRINT "        a. using IBM pc and Data Translation DT2805-DT707T board"
PRINT "           replace MST function generator"
PRINT "        b. control and collect test parameters at same time"
PRINT "    4. Notes: "
PRINT "        a. temperature preseted and controlled by the equipment of eurotherm"
PRINT "        b. vapor pressure measured and controlled by extra control part,"
PRINT "        c. initial vaccume condition is produced by a vaccume system,"
PRINT "        d. deformation is measured by a extra high quality LVDT."
PRINT

300 IF INKEY$ = "" THEN GOTO 300

400     'define constants.
DEFINT A-Z
BASE.ADDRESS = &H2EC
COMMAND.REGISTER = BASE.ADDRESS + 1
STATUS.REGISTER = BASE.ADDRESS + 1
DATA.REGISTER = BASE.ADDRESS
COMMAND.WAIT = &H4
WRITE.WAIT = &H2
READ.WAIT = &H5

500
CCLEAR = &H1
CERROR = &H2
CCLOCK = &H3
CSAD = &HD
CADIN = &HC
CRAD = &HE' + 128
CDAOUT = &H8 + 128
CSTOP = &HF
CRESET = &H1

TOP.RANGE# = 10
BOTTOM.RANGE# = -10

BASE.FACTOR# = 4096
BASE.CHANNELS = 8
GAIN(0) = 1
GAIN(1) = 10
GAIN(2) = 100
GAIN(3) = 500
```

```
600     'stop and clear the board
        OUT COMMAND.REGISTER, CSTOP
        TEMP = INP(DATA.REGISTER)
        WAIT STATUS.REGISTER, COMMAND.WAIT
        OUT COMMAND.REGISTER, CCLEAR

1000 ' set parameters

PRINT "TEST NUMBER (ONE ... ...) = ?";
INPUT NTST$

PRINT "NUMBER OF THERMOCOUPLES = ?";
INPUT NTHM

PRINT "NUMBER OF PRESSURE TRANSDUCERS = ?";
INPUT NPT

PRINT "NUMBER OF DISPLACEMENT TRANSDUCERS = ?";
INPUT NLVDT

1300 'selecte the dac channels.
PRINT "ENTER DESIRED DAC CHANNEL "; '(1 FOR PROGRAME CHECH AND 0 FOR OPERATION)";
PRINT "0 IS TO OPERATE MTS, 1 IS TO CHANGE LVDT RANGE."

1500
S = 1
PRINT "A/D START CHANNEL ( 1 TO 7 )"; S
ADSCHAN = S - 1
IF ADSCHAN < 0 THEN GOTO 1500
IF ADSCHAN > (BASE.CHANNELS - 1) THEN GOTO 1500

1600
ADECHAN = 7
PRINT "A/D END CHANNEL ( 1 TO 7 )"; ADECHAN
IF ADECHAN < 0 THEN GOTO 1600
IF ADECHAN > (BASE.CHANNELS - 1) THEN GOTO 1600

1700
NCHAN = ADECHAN - ADSCHAN + 1
NCHAN# = NCHAN
IF NCHAN < 1 THEN NCHAN = NCHAN + BASE.CHANNELS

2000  ' select procedures of operation
PRINT "SELECT PROCEDURES: "
PRINT "            1. GENERATE CONTROL DATA FILE "
PRINT "            2. SET REFERENCE DATA, "
PRINT "            3. TEST,"
PRINT "            4. EXIT"
INPUT sp$

SELECT CASE sp$
        CASE "1"
        PRINT "GENERATE CONTROL DATA FILE ..."
        genctda 32700, 32700
        GOTO 2000
        CASE "2"
        PRINT "GENERATE THE REFERENCE DATA ..."
        GOTO 2100
        CASE "3"
        PRINT " TEST !!!"
        GOTO 2200
        CASE "4"
        GOTO 10000
        CASE ELSE
        GOTO 2000
END SELECT

2100 'referenc data proceduce
        OPEN "a:datrf" + NTST$ FOR INPUT AS #1
```

```
GOTO 2500

2200 'open data file for output and input data
     OPEN "C:\mts\DATCT" + NTST$ FOR INPUT AS #1

2500 'input control data from the data file
     INPUT #1, alldat
     PRINT "ALLDAT ="; alldat

PRINT "TEST TIME (SECONDS) = ?"; alldat / 5

2600
ncon# = alldat
nconvers# = ncon#
IF nconvers# > 32700 THEN nconvers# = 32700
PRINT "NUMBER OF CONVERSIONS = ?"; nconvers#

2800     'dimension array to hold high and low byte of a/d data.
DIM ADL(NCHAN), ADH(NCHAN)
DIM AD#(nconvers# * 10)
DIM ctvolt(nconvers#)
DIM load#(nconvers#)

FOR j = 1 TO alldat
INPUT #1, z, load#(j)
NEXT j
CLOSE #1

3000
PRINT "                              START TEST   ???"

3100 IF INKEY$ = "" THEN GOTO 3100
CLS
LOCATE 10, 18, 1, 1
PRINT "TEST  STARTED  !!!   PLEASE  WAIT !!!";

3200   'check error
       WAIT STATUS.REGISTER, COMMAND.WAIT
       STATUS = INP(STATUS.REGISTER)
       IF (STATUS AND &H80) THEN GOTO 9500

       OUT COMMAND.REGISTER, CSTOP
       TEMP = INP(DATA.REGISTER)
       WAIT STATUS.REGISTER, COMMAND.WAIT
       OUT COMMAND.REGISTER, CCLEAR

3500 'start loop
BEEP
X! = TIMER
FOR I = 1 TO alldat

3600 'input control data from data file
       WAIT STATUS.REGISTER, COMMAND.WAIT
       STATUS = INP(STATUS.REGISTER)
       IF (STATUS AND &H80) THEN GOTO 9500

       OUT COMMAND.REGISTER, CSTOP
       TEMP = INP(DATA.REGISTER)
       WAIT STATUS.REGISTER, COMMAND.WAIT
       OUT COMMAND.REGISTER, CCLEAR

       DAVOLTS# = load#(I)

       RANGE# = TOP.RANGE# - BOTTOM.RANGE#
       DATA.VALUE# = (DAVOLTS# - BOTTOM.RANGE#) * 4096 / RANGE#
       DATA.VALUE# = CINT(DATA.VALUE#)
       IF DATA.VALUE# > 4095 THEN DATA.VALUE# = 4095
```

```
        'record control data
        ctvolt(I) = DATA.VALUE#

        WAIT STATUS.REGISTER, COMMAND.WAIT
        OUT COMMAND.REGISTER, CDAOUT

        WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
        OUT DATA.REGISTER, 0     ' DACSELECT

    'divide dac data into high and low bytes and write both bytes
    'to the data in register, waiting for a clear data in full flag
    'before each write.

        DAHIGH = INT(DATA.VALUE# / 256)
        DALOW = DATA.VALUE# - DAHIGH * 256
        WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
        OUT DATA.REGISTER, DALOW
        WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
        OUT DATA.REGISTER, DAHIGH

    'check error

        WAIT STATUS.REGISTER, COMMAND.WAIT
        STATUS = INP(STATUS.REGISTER)
        IF (STATUS AND &H80) THEN GOTO 9500

4000    'SET A/D PARAMETERS FOR TEMPERATURE MEASURE (gain of 3).
        'SET A/D PARAMETERS FOR PRESSURE AND POSITION MEASURE (gain of 0).

FOR q = 1 TO 10

IF q > 4 THEN GOTO 4020
ADCHANNEL = q - 1
ADGAIN = 3
LT = 0
GOTO 4060

4020
IF q <> 5 THEN GOTO 4030
ADCHANNEL = 4
ADGAIN = 0
LT = LT#
GOTO 4060

4030
IF q > 8 THEN GOTO 4050
ADCHANNEL = q - 1
ADGAIN = 0
LT = 0

4050
IF q <> 9 THEN GOTO 4055
ADCHANNEL = 4
ADGAIN = 1
LT = 0

4055
IF q <> 10 THEN GOTO 4060
ADCHANNEL = 4
ADGAIN = 2
LT = 0

4060
        'set a/d parameters command to set up the a/d converter.
        'wait until the board ready flag is set then write the
        'set a/d parameters command byte to the command register.

        WAIT STATUS.REGISTER, COMMAND.WAIT
        OUT COMMAND.REGISTER, CADIN
```

```
'wait until the board data in full flag is clear, then
'write the a/d gain byte to the data in register.

        WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
        OUT DATA.REGISTER, ADGAIN

'wait until board data in full flag is clear,
'write the a/d start channel byte to the dat in register.

        WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
        OUT DATA.REGISTER, ADCHANNEL

'read the A/D, high AND low BYTES, into arrays, waiting for a set
'data out ready (of ready) flag before each read.

4400
        WAIT STATUS.REGISTER, READ.WAIT
        ADL = INP(DATA.REGISTER)
        WAIT STATUS.REGISTER, READ.WAIT
        ADH = INP(DATA.REGISTER)
b = a + q

        AD#(b) = ADH * 256 + ADL + LT

        WAIT STATUS.REGISTER, COMMAND.WAIT
        STATUS = INP(STATUS.REGISTER)
        IF (STATUS AND &H80) THEN GOTO 9500

NEXT q
a = b
        WAIT STATUS.REGISTER, COMMAND.WAIT
        STATUS = INP(STATUS.REGISTER)
        IF (STATUS AND &H80) THEN GOTO 9500


' set up a control loop to feedback signal to LVDT cycle
' for entering a small measurment range.
4500
        IF I > 5 THEN GOTO 4900
        LVDTO# = -.01
        GOTO 4910
4900
        IF I < 9 THEN GOTO 4905
        LT# = (AD#(55) - AD#(85))

4905
        ' -.15 FOR P2, -.10 FOR P6, -.12 FOR P4
        LVDTO# = ((AD#(55) * (10 / 4096)) * 2 - 10) - .12

4910
        DAVOLTS# = LVDTO#

        RANGE# = TOP.RANGE# - BOTTOM.RANGE#
        DATA.VALUE# = (DAVOLTS# - BOTTOM.RANGE#) * 4096 / RANGE#
        DATA.VALUE# = CINT(DATA.VALUE#)
        IF DATA.VALUE# > 4095 THEN DATA.VALUE# = 4095

        WAIT STATUS.REGISTER, COMMAND.WAIT
        OUT COMMAND.REGISTER, CDAOUT

        WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
        OUT DATA.REGISTER, 1' DACSELECT

    'divide dac data into high and low bytes and write both bytes
    'to the data in register, waiting for a clear data in full flag
    'before each write.

        DAHIGH = INT(DATA.VALUE# / 256)
        DALOW = DATA.VALUE# - DAHIGH * 256
        WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
```

```
        OUT DATA.REGISTER, DALOW
        WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
        OUT DATA.REGISTER, DAHIGH

        'check error
        WAIT STATUS.REGISTER, COMMAND.WAIT
        STATUS = INP(STATUS.REGISTER)
        IF (STATUS AND &H80) THEN GOTO 9500

NEXT I

5000
Y! = TIMER
z! = Y! - X!
u! = z! / alldat
CLOSE #2

REDIM load#(0)
REDIM ADL(0), ADH(0)

BEEP
5100
        ' to set da channel 1 to output 0.
DAOUT# = -.01

        RANGE# = TOP.RANGE# - BOTTOM.RANGE#
        DATA.VALUE# = (DAOUT# - BOTTOM.RANGE#) * 4096 / RANGE#
        DATA.VALUE# = CINT(DATA.VALUE#)
        IF DATA.VALUE# > 4095 THEN DATA.VALUE# = 4095

5200
        WAIT STATUS.REGISTER, COMMAND.WAIT
        OUT COMMAND.REGISTER, CDAOUT

        WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
        OUT DATA.REGISTER, 1  ' DACSELECT

    'divide dac data into high and low bytes and write both bytes
    'to the data in register, waiting for a clear data in full flag
    'before each write.

        DAHIGH = INT(DATA.VALUE# / 256)
        DALOW = DATA.VALUE# - DAHIGH * 256
        WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
        OUT DATA.REGISTER, DALOW
        WAIT STATUS.REGISTER, WRITE.WAIT, WRITE.WAIT
        OUT DATA.REGISTER, DAHIGH

        'check error
        WAIT STATUS.REGISTER, COMMAND.WAIT
        STATUS = INP(STATUS.REGISTER)
        IF (STATUS AND &H80) THEN GOTO 9500

        OUT COMMAND.REGISTER, CSTOP
        TEMP = INP(DATA.REGISTER)
        WAIT STATUS.REGISTER, COMMAND.WAIT
        OUT COMMAND.REGISTER, CCLEAR

5300
CLS

LOCATE 5, 10, 1, 1
PRINT "        T E S T   C O M P L E T E    !"
LOCATE 15, 10
PRINT "DATA CONVERSION IS IN PROGRESS !   PLEASE WAIT !!!"
LOCATE 22, 10
PRINT "        TIME FOR PREPARING NEXT TEST  !!!"
LOCATE 25
PRINT
```

```
5600    'calculate and print all converted a/d voltages,
        'formatting the spacing to indicate first and last channel readings.

5900
        WAIT STATUS.REGISTER, COMMAND.WAIT
        STATUS = INP(STATUS.REGISTER)
        IF (STATUS AND &H80) THEN GOTO 9500

6000    OPEN "C:\data\DIGDAT" + NTST$ FOR OUTPUT AS #4
        IF sp$ = "2" THEN
             OPEN "A:datarf" + NTST$ FOR OUTPUT AS #3
        ELSE OPEN "C:\MTS\DATA" + NTST$ FOR OUTPUT AS #3
        END IF
6050
        'set values for system of thermocouples,pressure and LVDT

    'SENPT = sensitivity of pressure transducers (PSI/VOLT)
    'SENLT = sensitivity of position transducers (in/volt)

6100
        SENPTVP# = ((150 / 14.2) / 10.2) / 10 'vapor pressure (MPa/V)
        SENPTLP# = ((5000 / (3.1415 * 9.2 * 9.2 / 4)) / 10.2) / 10 ' (MPa/M2)/V
        SENLT1# = 25.4 / 10       'LVDT position   (mm/V)
        SENLT2# = 25.4 / 2         'piston position (mm/V)

6150 'ZEROVP! = zero output of vapor pressure trans in volts
     'ZEROLP! = zero output of lead pressure trans in volts
     'ZEROLT! = zero output of lved in volts


6200    'start loop to concider data for each cycle
        ZEROVP# = 0
        ZEROLP# = 0
        LVREF1# = 9.36  '2.239  'lvrf1!
        LVREF2# = 4  '13.29 '12.29  'lvrf2!

6300
        OUT COMMAND.REGISTER, CSTOP
        TEMP = INP(DATA.REGISTER)
        WAIT STATUS.REGISTER, COMMAND.WAIT
        OUT COMMAND.REGISTER, CCLEAR

FOR eloop = 1 TO nconvers#

6500  'select thermocouple channels

ADGAIN = 3
FACTOR# = (10 / BASE.FACTOR#) / GAIN(ADGAIN)

FOR CHANT = 1 TO 4
'calculate the a/d reading in volts.
b = (eloop - 1) * 10 + CHANT
        UNI.VOLTS# = AD#(b) * FACTOR#
        BI.VOLTS# = UNI.VOLTS# * 2 - (10 / GAIN(ADGAIN))
        TRAW# = BI.VOLTS#
        IF CHANT <> 1 THEN GOTO 6700
6600  'obtain reference cold junction voltage
        CJV# = TRAW#
        CJT# = CJV# * 1000! / .5
        CJREF# = 38.66698 * CJT# + 4.373944E-02 * (CJT# ^ 2!) - 2.497418E-05 * (CJT# ^ 3!)

6700  'obtain voltage for current channel
        VNT# = TRAW#

6750    'apply cold juntion corrected voltage (IN MICROVOLTS)
        VF# = (VNT# * 1000000!) + CJREF#

6800  'apply cubic conversion factors to get temperature
        TEMP# = 2.507424E-02 * VF# - 4.492068E-07 * (VF# ^ 2!) + 7.994254E-12 * (VF# ^ 3!)
```

```
6900  'save results in data file and print on screen
        IF CHANT = 2 THEN
        PRINT #3, USING "####.##,"; TEMP#;
        END IF
6950
NEXT CHANT

7200
ADGAIN = 0
FACTOR# = (10 / BASE.FACTOR#) / GAIN(ADGAIN)

        'calculate the a/d reading in volts.
FOR CHANP = 5 TO 8  'press and vapor data
        'obtain voltage for current channel

c = (eloop - 1) * 10 + CHANP

        UNI.VOLTS# = AD#(c) * FACTOR#
        BI.VOLTS# = UNI.VOLTS# * 2 - (10 / GAIN(ADGAIN))
        VNP# = BI.VOLTS#

7300        'calculate pressure
        IF (CHANP = 5) THEN
                THICK1# = (LVREF1# + VNP#) * SENLT1#
                THICK1# = THICK1# - PIST#
                PRINT #3, USING "##.#####,"; THICK1#;
                'strain! = 18 - THICK1#
                strain! = 12 - THICK1#
                PRINT #4, USING "##.#####,"; strain!;
                'PRINT #4, AD#(c);
                IF eloop = 10 THEN THRF# = THICK1#
        ELSEIF (CHANP = 6) THEN
                PRESVP# = (VNP# - ZEROVP#) * SENPTVP#
                PRINT #3, USING "####.####,"; PRESVP#;
'                PRINT #4, AD#(c);
        ELSEIF (CHANP = 7) THEN
                THICK2# = (LVREF2# + VNP#) * SENLT2#
                PRINT #3, USING "###.####,"; THICK2#;
                'PRINT #4, AD#(c);
                IF eloop = 6 THEN MTS# = THICK2#
                IF eloop = 9 THEN MS# = MTS# - THICK2#
                PIST# = MS#
        ELSEIF (CHANP = 8) THEN
                PRESLP# = -(VNP# - ZEROLP#) * SENPTLP#
                PRINT #3, USING "##.####,"; PRESLP#;
                'PRINT #4, AD#(c);
        END IF

7370
NEXT CHANP

7380
ADGAIN = 1
FACTOR# = (10 / BASE.FACTOR#) / GAIN(ADGAIN)
        'calculate the a/d reading in volts.
c = (eloop - 1) * 10 + 9
        UNI.VOLTS# = AD#(c) * FACTOR#
        BI.VOLTS# = UNI.VOLTS# * 2 - (10 / GAIN(ADGAIN))
        LT1# = BI.VOLTS#
                THICK# = (LT1#) * SENLT1#
                IF eloop = 10 THEN T1# = THICK#
                TH1# = T1#
                THICK9# = THRF# - (TH1# - THICK#)
                PRINT #3, USING "##.#####,"; THICK9#;
                'PRINT #4, AD#(c);

7390
ADGAIN = 2
FACTOR# = (10 / BASE.FACTOR#) / GAIN(ADGAIN)
```

```
                'calculate the a/d reading in volts.
c = (eloop - 1) * 10 + 10
        UNI.VOLTS# = AD#(c) * FACTOR#
        BI.VOLTS# = UNI.VOLTS# * 2 - (10 / GAIN(ADGAIN))
        LT1# = BI.VOLTS#
                THICK# = (LT1#) * SENLT1#
                IF eloop = 10 THEN T2# = THICK#
                TH2# = T2#
                THICKO# = THRF# - (TH2# - THICK#)
                PRINT #3, USING "##.#####,"; THICKO#;
                'strain! = 18 - THICKO#
                strain! = 12 - THICKO#
                PRINT #4, USING "##.#####,"; strain!;
                'PRINT #4, AD#(c);

7400    'record control data
st! = (5000 / (3.1415 * 9.2 * 9.2 / 4)) / 10.2
R! = st! / 10
        ctv# = ctvolt(eloop) * RANGE# / 4096
        ctp# = -(ctv# + BOTTOM.RANGE#) * R!
        IF eloop = ctvolt THEN ctp# = 0
        PRINT #3, USING "##.####"; ctp#;

7500    'record each loop test time
        'calculate each loop time
        TIME! = eloop * .2

        PRINT #3, USING "####.##,"; TIME!
        PRINT #4, USING "####.##,"; TIME!
        'PRINT #4, TIME!


7800
NEXT eloop
CLOSE #3
CLOSE #4

7900 'print out time of total and each loop
PRINT u!, w! - V!
8200
IF sp$ = "2" THEN 2000
9500    'program error explain
        'stop the dt2805 board and empty the data out register
        'wait until the dt2805 board ready flag is set,
        'then write the read error register command byte
        'to the command register
        OUT COMMAND.REGISTER, CSTOP
        TEMP = INP(DATA.REGISTER)
        WAIT STATUS.REGISTER, COMMAND.WAIT
        OUT COMMAND.REGISTER, CERROR

'wait until the dt2805 board data out ready flag is set,
'then read the dataout register to get the error register low byte
        WAIT STATUS.REGISTER, READ.WAIT
        ERR1 = INP(DATA.REGISTER)

'wait until the dt2805 board data out ready flage is set,
'then read the data out register to get the error register high byte.
        WAIT STATUS.REGISTER, READ.WAIT
        ERR2 = INP(DATA.REGISTER)

'check the error flag.
        IF ERR1 > 0 THEN
        PRINT "PROGRME ERR ARE:"
        PRINT "ERR1 ="; ERR1
        ELSEIF ERR2 > 0 THEN
        PRINT "PROGRME ERR ARE:"
        PRINT "ERR2 ="; ERR2
        END IF
```

```
10000
END

SUB genctda (alldat!, load!) STATIC

' this is the part 3 of a composites manufacturing simulation test system
' this program is for creating a data file
' and the file will be used to control mts machine
'
CLS
LOCATE 5, 10
PRINT "  WELCOME TO COMPOSITES MANUFACTURING SIMULATION TEST SYSTEM"
LOCATE 10, 10
PRINT "                      PART III "
LOCATE 15
PRINT
PRINT "        ************************************************"
PRINT "        *                                          * "
PRINT "        *      MTS CONTROL DATA GENERATING PROGRAM !   *"
PRINT "        *                                          *"
PRINT "        ************************************************        "
10050 IF INKEY$ = "" THEN GOTO 10050
CLS
LOCATE 2
PRINT
'DIM load!(alldat)
'DIM pload!(alldat)

10100 'creat a data file
PRINT "DATA FILE SELECT:"
PRINT
PRINT "        1. MTS TEST REFERENC DATA,"
PRINT "        2. MTS TEST CONTROL DATA"
PRINT "        3. EXIT"
INPUT sf$
10150
PRINT " DATA FILE NUMBER =        ? "
INPUT ndaf$

SELECT CASE sf$
        CASE "1"
                PRINT " Reference data file generation !"
                GOTO 10200
        CASE "2"
                PRINT "Test control data file generation !"
                GOTO 10300
        CASE "3"
                PRINT "EXIT SUB  !"
                GOTO 10900
        CASE ELSE
                GOTO 10100
END SELECT

10200
OPEN "a:rfct" + ndaf$ FOR OUTPUT AS #1
GOTO 10400
10300
OPEN "C:\MTS\datct" + ndaf$ FOR OUTPUT AS #1

10400
PRINT " how many test stages =     ?"
INPUT stage

PRINT " totle test time =      (sec.) ? "
INPUT tt

alldat = tt * 5
PRINT #1, alldat
PRINT alldat
```

```
PRINT " diameter of test disks =  (mm)"
INPUT disk!
a! = (3.1415 * 9.2 * 9.2 / 4)
st! = (5000 / a!) / 10.2 'maximum stress m(N/M2)
PRINT "maximum stress = "; st!
R! = st! / 10
10500
FOR I = 1 TO stage
        PRINT "the "; I; "stage of "; stage; " pressing time = ?   "
        INPUT timstg!
        PRINT "start press pressure =  (m(N/M2)) "
        INPUT ps!
        pstart! = ps! / R!
        PRINT "end press pressure = (mN/M2)) "
        INPUT pe!
        pend! = pe! / R!
10600
        'taveg!(i) = (tend(i) - tstart(i)) / timstg
        pdiff! = (pend! - pstart!)
        peach! = pdiff! / (timstg! * 5)

IF I = 1 THEN tm = 1
FOR j = tm TO (timstg! * 5 + tm - 1)

        IF pend! <> pstart! THEN
                pvalue! = pstart!
        ELSE
                pvalue! = pend!
        END IF
                each! = peach! * (j - tm + 1)
                pload! = pvalue! + each!
                load! = pload!

        PRINT #1, j, load!
'         PRINT J, load!
NEXT j
tm = j
IF ((j - 1) / 5) >= tt THEN 10650

NEXT I

10650
CLOSE #1

10700 ' check time and data numbers

PRINT " totel time  =   ?"; j - 1
d = 5 * tt
PRINT " totel data  =   ?"; d

IF ((j - 1) / 5) <> tt THEN
PRINT " setted wroung time !!!"
ELSEIF d <> alldat THEN
PRINT "setted wroung data !!!";
END IF

10900

END SUB
```

```
            PROGRAM CST.FOR
C*********************************************************
c this program calculates the rheological constants
c of wood-adhesive system during hot pressing from
c experimental results, and to creat a E1, E1P, K1 data file
c for futher analysis.
c 7-26-1990 by Shan Ren, improved on 2-2-1991
C*********************************************************
            REAL*8 (A-H,O-Z)
            REAL*8 th(630*5),Strs(630*5)
            CHARACTER*3 U
            CHARACTER*2 N$
            CHATATER*4 W,V
            CHARACTER*5 X,Z
            CHARACTER*6 Y
            WRITE(*,*) 'NUMBER OF TEST = '
            READ(*,*) N$
            WRITE(*,*) 'CONDITION OF TEST'
            READ(*,*) NC$
            U='DEF'
            V='CTE1'
            W='E1P'
            X=U // N$
            Y=V // N$
            Z=W // N$
            OPEN(UNIT=7,FILE='C:\SHAN\X')
            OPEN(UNIT=8,FILE='C:\SHAN\Y')
            OPEN(UNIT=9,FILE='C:\SHAN\Z')
c       input data
            N=630*5
            DO 100 I=1,N
              READ(7,*)TIME,TH(I),STRS(I)
100     CONTINUE
            CLOSE(UNIT=7)
            WRITE(8,*)'Te No=','N$','INTI H 0.2=',TH(1),'1='TH(5)
            WRITE(8,*)'TIME,LOAD,DENSITY,THICK,E1,STRAIN,STRESS '
c       calculate of elastic element 1:   ";
c       calculate the elastisity of elastic element 1 at vary c      condition.
c       Strain = Stress / E
            DO 200 I=23,63,40
              T=I*5
              AVT1=(TH(T)+TH(T-1)+TH(T-2))/3
              AVT2=(TH(T+1)+TH(T+2)+TH(T+3))/3
              STN1=(AVT1-AVT2)/AVT1
              STS1=STRS(T)-STRS(T+1)
              IF(Stn1.EQ.0) THEN GOTO 150
              E1=ABS(STS1/STN1)
              DENS=(140000 /((3.14156*9.2*9.2/4)*AVT1)
150         CONTINUE
              WRITE(8,'F4.1') T/5
              WRITE(8,'F6.4') STRS(T)
              WRITE(8,'F9.5') DENS
              WRITE(8,'F9.6') AVT1
              WRITE(8,'F13.6') E1
              WRITE(8,'F8.5,1X,F8.5)') STN1,STS1
200     CONTINUE
c       for i > 265
            DO 300 T=1325,1335
              STN1=(TH(T)-TH(T+1))/TH(T)
              STS1=STRS(T)-STRS(T+1)
              IF(STN1.EQ.0) THEN GOTO 250
              IF(T.GT.1325) THEN STS1=-STS1
              E1=(STS1/STN1)
              DENS=(140000)/((3.14156*9.2*9.2/4)*TH(T))
250         CONTINUE
              WRITE(8,'F4.1') t/5
              WRITE(8,'F6.4') Strs(t)
              WRITE(8,'F9.5') dens
              WRITE(8,'F9.6') th(t)
              WRITE(8,'F13.6') E1
              WRITE(8,'F8.5,1X,F8.5') Stn1,Sts1
300     CONTINUE
```

```
c       for elasitical element 1: E1 at 307.2 sec.
        DO 400 T=1536,2936,200
          AVT1=(TH(T)+TH(T-1)+TH(T-2))/3
          AVT2=(TH(T+1)+TH(T+2)+TH(T+3))/3
          STN1=(AVT1-AVT2)/AVT1
          STS1=STRS(T)-STRS(T+1)
          IF(STN1.EQ.0) THEN GOTO 350
          E1=(STS1/STN1)
          DENS=(140000)/((3.14156*9.2*9.2/4)*AVT1)
350       CONTINUE
          WRITE(8,'F4.1') t/5
          WRITE(8,'F6.4') Strs(t)
          WRITE(8,'F9.5') dens
          WRITE(8,'F9.6') avt1
          WRITE(8,'F13.6') E1
          WRITE(8,'F8.5,1X,F8.5') Stn1,Sts1
400     CONTINUE
c       for elasitical element 1: E1 at 589.2 sec.
        STN1=(TH(2945)-TH(2946))/TH(2945)
        STS1=STRS(2945)-STRS(2946)
        IF(STN1.EQ.0) THEN GOTO 500
        E1=ABS(STS1/STN1)
        DENS=(140000)/((3.14156*9.2*9.2/4)*TH(2945))
500     CONTINUE
        WRITE(8,'F4.1') 589.2/5
        WRITE(8,'F6.4') Strs(2945)
        WRITE(8,'F9.5') dens
        WRITE(8,'F9.6') th(2945)
        WRITE(8,'F13.6') E1
        WRITE(8,'F8.5,1X,F8.5') Stn1,Sts1
c       Calculate the E1P:
c       E1P = Stress / Strain
c       Strain=Stress/P+Stress/E1=Stress((E1+P)/P*E1)
c       P = 1/(1/E1P - 1/E1)
        WRITE(9,*)'TIME,STRESS,DENSITY,THICK,E1P,STRAIN,STS1'
        DO 600 T=1,6
          STN1=(TH(T)-TH(T+1))/TH(T)
          STS1=STRS(T)-STRS(T+1)
          IF(STN1.EQ.0) THEN GOTO 550
          E1P=(STS1/STN1)
          DENS=(140000)/((3.14156*9.2*9.2/4)*TH(T))
550       CONTINUE
          WRITE(9,'F4.1') T/5
      .   WRITE(9,'F6.4') STRS(T)
          WRITE(9,'F9.5') DENS
          WRITE(9,'F9.6') TH(T)
          WRITE(9,'F13.6') E1P
          WRITE(9,'F8.5,1X,F8.5') STN1,STS1
600     CONTINUE
        DO 700 T=10,15
          STN1=(TH(T)-TH(T+1))/TH(T)
          STS1=STRS(T)-STRS(T+1)
          IF(STN1.EQ.0) THEN GOTO 650
          E1P=(STS1/STN1)
          DENS=(140000)/((3.14156*9.2*9.2/4)*TH(T))
650       CCONTINUE
          WRITE(9,'F4.1') T/5
          WRITE(9,'F6.4') STRS(T)
          WRITE(9,'F9.5') DENS
          WRITE(9,'F9.6') TH(T)
          WRITE(9,'F13.6') E1P
          WRITE(9,'F8.5,1X,F8.5') STN1,STS1
700     CONTINUE
c       for elasitical element 1 and plastic element: E1P at
c       123 sec.
        STN1=(TH(615)-TH(616))/TH(615)
        STS1=STRS(615)-STRS(616)
        IF(STN1.EQ.0) THEN GOTO 800
        E1P=STS1/STN1
        DENS123=(140000)/((3.14156*9.2*9.2/4)*TH(615))
800     CONTINUE
        WRITE(9,'F4.1') 123
```

```
          WRITE(9,'F6.4') STRS(615)
          WRITE(9,'F9.5') DENS
          WRITE(9,'F9.6') TH(615)
          WRITE(9,'F13.6') E1P
          WRITE(9,'F8.5,1X,F8.5') STN1,STS1
c         when i < 265
          DO 900 T=1315,1325
             STN1=(TH(T)-TH(T+1))/TH(T)
             STS1=STRS(T)-STRS(T+1)
             IF(STN1.EQ.0) THEN GOTO 850
             E1P=(STS1/STN1)
             DENS=(140000)/(3.14156*9.2*9.2/4)*TH(T))
850          CONTINUE
             WRITE(9,'F4.1') T/5
             WRITE(9,'F6.4') STRS(T)
             WRITE(9,'F9.5') DENS
             WRITE(9,'F9.6') TH(T)
             WRITE(9,'F13.6') E1P
             WRITE(9,'F8.5,1X,F8.5') STN1,STS1
900       CONTINUE
c         calculate the visco element 1: k1
c         ek1 = Strs*t / K1 ; K1 = Strs*t/ek1
c         CALCULATE OF ELASTIC ELEMENTS  2  =  ";
c         stn = stnk1 + stne2
c         stnk1 = Sts*t/K1 = (he1-h2)/he1
c         the2 = (tht!/(1-stnk1))
          WRITE(8,*)'TIME, STRESS, DENSITY, THICK, K1, E '
          DO 1000 I=200,260,5
             T=I*5
             TH=ABS(TH(T-1)+TH(T)+TH(T+1))/3
             THA=ABS(TH(T+24)+TH(T+25)+TH(T+26))/3
             DENS=(140000)/((3.14156*9.2*9.2/4)*TH)
             STNK1=ABS(TH-THA)/TH
             THK1=ABS(TH/(1-STNK1))
             IF((TH-THA).EQ.0) THEN GOTO 950
             K1=(STRS(T)*5)/STNK1
             THKAP=ABS((TH-THA)/5)
             KAP=STRS(T)/K1
950          CONTINUE
             WRITE(8,'F 4.1') I
             WRITE(8,'F6.4') STRS(T)
             WRITE(8,'F9.5') DENS
             WRITE(8,'F9.6') TH
             WRITE(8,'F13.6') K1
             DTHE2=THK1-THA
             THE2=TH-DTHE2
             STNE2=(DTHE2)/TH
             IF(STNE2.EQ.0) THEN GOTO 980
             E2=ABS(STRS(T)/STNE2)
980          CONTINUE
             WRITE(8,'F12.6') E2
1000      CONTINUE

          DO 1100 I=150,260,10
             T=I*5
             TH=ABS(TH(T-1)+TH(T)+TH(T+1))/3
             THA=ABS(TH(T+49)+TH(T+50)+TH(T+51))/3
             DENS=(140000)/((3.14156*9.2*9.2/4)*TH)
             STNK1=ABS(TH-THA)/TH
             THK1=ABS(TH/(1-SNK1))
             IF((TH-THA).EQ.0) THEN GOTO 1050
             K1=(STRS(T)*10)/STNK1
             THKAP=ABS((TH-THA)/10)
             KAP=STRS(T)/K1
1050         CONTINUE
             WRITE(8,'F 4.1') i
             WRITE(8,'F6.4') Strs(t)
             WRITE(8,'F9.5') dens
             WRITE(8,'F9.6') th
             WRITE(8,'F13.6') K1
             DTHE2=THK1-THA
             THE2=TH-DTHE2
```

```
      STNE2=(DTHE2)/TH
      IF(STNE2.EQ.0) THEN GOTO 1080
      E2=ABS(STRS(T)/STNE2)
1080    WRITE(8,'F12.6') E2
1100  CONTINUE
      CLOSE(UNIT=8)
      CLOSE(UNIT=9)
      STOP
      END
```

```fortran
       PROGRAM CSTE2.FOR
C***********************************************************
c  this program is to calculate the rheological constants
c  of wood-adhesive system during hot pressing from
c  experimental results, and to creat an E2 data file
c  for futher analysis.
c  7-26-1990 by Shan Ren, improved on 2-2-1991
C***********************************************************
       REAL*8 (A-H,O-Z)
       REAL*8 TH(300*5), STRS(300*5)
       CHARACTER*3 NC$, U,V
       CHARACTER*2 N$
       CHATATER*4 W
       CHARACTER*5 X
       CHARACTER*6 Y,Z
       WRITE(*,*) 'NUMBER OF TEST = '
       READ(*,*) N$
       WRITE(*,*) 'CONDITION OF TEST'
       READ(*,*) NC$
       U='ALC'
       V='DEF'
       W='CSET'
       X=U // NC$
       Y=V // N$
       Z=W // N$
       OPEN(UNIT=7,FILE='C:\SHAN\X')
       OPEN(UNIT=8,FILE='C:\SHAN\Y')
       OPEN(UNIT=9,FILE='C:\SHAN\Z')
c      input parameters
       READ(7,*) AE1, BE1, AP, BP, AK1, BK1
       CLOSE(UNIT=7)
c      input data
       N=300*5
       DO 100 I=1,N
         READ(8,*) TIME, TH(I), STRS(I)
100    CONTINUE
       CLOSE(UNIT=8)

c      CALCULATE OF ELASTIC ELEMENT 2:   ";
c      at t >> t0, ee2 = eetotal-ee1-ek1-ep, ee2k2 = 0
c      stn = stnk1 + stne2
       WRITE(9,*) 'TEST NUMBER =', 'N$'
       WRITE(9,*)'TIME, DENSITY, LOAD, THICK, THICKC, E2'
       DO 200 I=50,300,5
         T=I*5
         TH=(TH(T-1)+TH(T)+TH(T+1))/3
         THB=(TH(T-24)+TH(T-25)+TH(T-26))/3
         DENS=(140000)/((3.14156*9.2*9.2/4)*)
c      Calculate the each element constant:
c
c
       E1=EXP(AE1+BE1*DENS)
       P=EXP(AP+BP*DENS)
       K1=EXP(AK1+BK1*DENS)
c
c      calculate the ee1:
       EE1=(STRS(T)-STRS(T - 25))/E1

       THE1=(TH*(1-EE1))
       DTHE1=(TH-THE1)
c      calculate the ep:
c      check maximin value of stress:
       IF (SM.LE.STRS(T)) THEN SM=STRS(T)
       ST=SM
       IF(SM.GT.STRS(T)) THEN ST=SM
       ST1=ST-STRS(T-25)
       EP=ST1/P

       THP=(TH*(1-EP))
       DTHP=(TH-THP)
       IF (STM.GE.STRS(T)) THEN DTHP=0
       STM=ST
```

```
c          calculate the ek1:
           EK1=STRS(T)*25/K1
           THK1=ABS(TH*(1 - EK1))
           DTHK1=ABS(THK1 - TH)
c          calculate the EE2:
           ETOTAL=ABS(TH-THB)/TH
           EE2=ABS(ETOTAL-EE1-EP-EK1)
           THE2=ABS(TH*(1-EE2))
           DTHE2=ABS(THE2-TH)
           IF(EE2.EQ.0) THEN GOTO 150
           E2=(STRS(T)/EE2)
c          CALCULATE THE DEFORMATION:
           DTH=(DTHE1+DTHP+DTHE2+DTHK1)
           THA=TH-DTH
150        CONTINUE
           WRITE(9,'F4.1') T
           WRITE(9,'F6.4') STRS(T)
           WRITE(9,'F8.4') DENS
           WRITE(9,'F8.6,1X,F8.6') TH,THA
           WRITE(9,'F12.6') E2
200        CONTINUE
           STOP
           END
```

```
       PROGRAM CSTK2.FOR
c*************************************************************
c this program calculates the rheological constants of
c wood-adhesive system during hot pressing from
c experimental results and to creat a K2 data file
c for futher analysis.
c 7-26-1990 by Shan Ren, improved on 2-2-1991
c*************************************************************
       REAL*8 (A-H,O-Z)
       REAL*8 TH(300*5),STRS(300*5)
       CHARACTER*2 N$
       CHARACTER*3 NC$
       CHARACTER*4 W
       CHARACTER*5 X
       CHARACTER*6 Y,Z
       WRITE(*,*)'NUMBER OF TEST = '
       READ(*,*) N$
       WRITE(*,*)'CONDITION OF TEST = '
       READ(*,*) NC$
       U='ALC'
       V='DEF'
       W='CSTK'
       X=U//NC$
       Y=V//N$
       Z=W//N$
       OPEN(UNIT=7,FILE='C:\SHAN\X')
       OPEN(UNIT=8,FILE='C:\SHAN\Y')
       OPEN(UNIT=9,FILE='C:\SHAN\Z')
c      input parameters
       READ(7,*)AE1,BE1,AP,BP,AK1,BK1,AE2,BE2
       CLOSE(UNIT=7)
c      input data
       N=300*5
       DO 100 FOR I=1,N
          READ(8,*)TIME,TH(I),STRS(I)
100    CONTINUE
       CLOSE(UNIT=8)
c      CALCULATE THE VISCO ELEMENT 2: K2
c      ee2k2 = etotal-ee1-ee2-ek1-ep
c      ee2k2' =S/K1 + S / K2 * (e(-E2*t/K2))
c      K2 = E2*t*log(e)/(log(strs/E2)-log( *** ))
       WRITE(9,*)'TEST NUMBER =', 'N$'
       WRITE(9,*)'TIME, LOAD, DENSITY, THICH, THKC, K2'
       DO 200 I=50,300,5
          T=I*5
          TH=(TH(T-1)+TH(T)+TH(T+1))/3
          THB=(TH(T-24)+TH(T-25)+TH(T-26))/3
          DENS=(140000)/((3.14156*9.2*9.2/4)*TH)
c         Calculate the each element constant:
c
c
          E1=EXP(AE1+BE1*DENS)
          P=EXP(AP+BP*DENS)
          K1=EXP(AK1+BK1*DENS)
          E2=EXP(AE2+BE2*DENS)
c
c         calculate the ee1:
          EE1=(STRS(T)-STRS(T-25))/E1

          THE1=(TH*(1-EE1))
          DTHE1=(TH-THE1)
c         calculate the ep:
c         check maximin value of stress:
          IF(SM.LE.STRS(T)) THEN SM=STRS(T)
          ST=SM
          IF(SM.GT.STRS(T)) THEN ST=SM
          ST1=ST-STRS(T - 25)
          EP=ST1/P

          THP=(TH*(1-EP))
          DTHP=(TH-THP)
          IF(STM.GT.STRS(T)) THEN DTHP=0
```

```
        STM=ST
c       calculate the ek1:
        EK1=STRS(T)*25/K1
        THK1=ABS(TH*(1-EK1))
        DTHK1=ABS(THK1-TH)
c       calculate the ee2:
        EE2=(STRS(T)/E2)
        THE2=ABS(TH*(1-EE2))
        DTHE2=ABS(THE2-TH)
c       calculate the EV2:
        ETOTAL=ABS(TH-THB)/TH
        E2K2=ABS(ETOTAL-EE1-EE2-EK1-EP)
        THE2K2=ABS(TH*(1+E2K2))
        DTHE2K2=ABS(THE2-TH)
        L=LOG(E2*E2K2/STRS(T))
        IF (L.EQ.0) THEN GOTO 150
        K2=(E2*25)/(L)
c       calculate the deformation:
150     CONTINUE
        DTH=(DTHE1+DTHP+DTHE2+DTHK1-DTHE2K2)
        THA=TH-DTH
        WRITE(9,'4.1') T
        WRITE(9,'F6.2') STRS(T)
        WRITE(9,'F8.4') DENS
        WRITE(9,'F8.6,1X,F8.6') TH,THA
        WRITE(9,'F12.6') K2
200     CONTINUE
        CLOSE(UNIT=8)
        STOP
        END
```

```
       PROGRAM CSTP.FOR
c*****************************************************************
c this program calculates the rheological constants
c of wood-adhesive system during hot pressing from
c experimental results and to creat E1P and P data file
c for futher analysis.
c 7-26-1990 by Shan Ren, improved on 2-2-1991
c*****************************************************************
       READ*8 (A-H,O-Z)
       REAL*8 TH(270*5),STRS(270*5),A(27*5)
       CHARACTER*2 N$
       CHARACTER*3 NT$
       CHARACTER*4 W
       CHARACTER*5 X
       CHARACTER*6 Y,Z
       WRITE(*,*)'NUMBER OF TEST ='
       READ(*,*)N$
       WRITE(*,*)'CONDITION OF TEST = '
       READ(*,*)NT$
       U='ACL'
       V='DEF'
       W='CSTP'
       X=U//NT$
       Y=V//N$
       Z=W//N$
       OPEN(UNIT=7,FILE='C:\SHAN\X')
       OPEN(UNIT=8,FILE='C:\SHAN\Y')
       OPEN(UNIT=9,FILE='C:\SHAN\Z')
c      input parameters of E1 from equation
       READ(7,*)AE1,BE1
       CLOSE(UNIT=7)
c      input data
       N=270*5
       DO 100 I=1,N
         READ(8,*)TIME, TH(I),STRS(I)
100    CONTINUE
       CLOSE(UNIT=8)
c      Calculate the E1P:
c      E1P = Stress / Strain
c      Strain = Stress/P + Stress/E1 = Stress ((E1+P)/P*E1)
c      P = 1/(1/E1P - 1/E1)
       WRITE(9,*)'Te No=','N$','int h 1=' (1), th(5)
       WRITE(9,*)'time,load,density,thick,P,E1c,Strain,Sts1'
       DO 200 T = 1 TO 6
         dens=(140000)/((3.14156*9.2*9.2/4)*th(t))
         Stn1=(th(t)-th(t+1))/th(t)
         Sts1=Strs(t)-Strs(t+1)
         IF(Stn1.EQ.0) THEN GOTO 150
         E1P=(Sts1/Stn1)
         E1c=EXP(ae1+be1*dens)
         IF(E1P.EQ.0) THEN GOTO 150
         P=1/(1/E1P-1/E1c)
150      WRITE(9,'F4.1') t/5
         WRITE(9,'F6.4') Strs(t)
         WRITE(9,'F8.4') dens
         WRITE(9,'F8.6') th(t);
         WRITE(9,'F12.6,1X,F12.6') P,E1c
         WRITE(9,'F8.5,1X,F8.5') Stn1,Sts1
200    CONTINUE
       DO 300 T=10,15
         DENS=(140000)/((3.14156*9.2*9.2/4)*TH(T))
         STN1=(TH(T)-TH(T+1))/TH(T)
         STS1=STRS(T)-STRS(T+1)
         IF(STN1.EQ.0) THEN GOTO 250
         E1P=(STS1/STN1)
         E1C=EXP(AE1+BE1*DENS)
         IF(E1P.EQ.0) THEN GOTO 250
         P=1/(1/E1P-1/E1C)
250      CONTINUE
         WRITE(9,'F4.1') T/5
         WRITE(9,'F6.4') STRS(T)
         WRITE(9,'F8.4') DENS
```

```
          WRITE(9,'F8.6') TH(T)
          WRITE(9,'F12.6,1X,F12.6') P,E1C
          WRITE(9,'F8.5,1X,F8.5') STN1,STS1
300    CONTINUE
c      for elasitical element 1 and plastic element: E1P at c   c      123 sec.
       DENS=(140000)/((3.14156*9.2*9.2/4)*TH(615))
       STN1=(TH(615)-TH(616))/TH(615)
       STS1=STRS(615)-STRS(616)
       IF(STN1.EQ.0) THEN GOTO 400
       E1P=(STS1/STN1)
       E1C=EXP(AE1+BE1*DENS)
       IF(E1P.EQ.0 THEN) GOTO 400
       P=1/(1/E1P-1/E1C)
400    WRITE(9,'F4.1') 123
       WRITE(9,'F6.4') STRS(615)
       WRITE(9,'F8.4') DENS
       WRITE(9,'F8.6') TH(615)
       WRITE(9,'F12.6,1X,F12.6') P,E1C
       WRITE(9,'F8.5,1X,F8.5') STN1,STS1
c      when i < 265
       DO 500 T=1315,1325
          DENS=(140000)/((3.14156*9.2*9.2/4)*TH(T))
          STN1=(TH(T)-TH(T+1))/TH(T)
          STS1=STRS(T)-STRS(T+1)
          IF(STN1.EQ.0) THEN GOTO 450
          E1P=(STS1/STN1)
          E1C=EXP(AE1+BE1*DENS)
          IF(E1P.EQ.0) THEN GOTO 450
          P=1/(1/E1P-1/E1C)
450       WRITE(9,'F4.1') T/5
          WRITE(9,'F6.4') STRS(T)
          WRITE(9,'F8.4') DENS
          WRITE(9,'F8.6') TH(T)
          WRITE(9,'F12.6,1X,F12.6') P,E1C
          WRITE(9,'F8.5,1X,F8.5') STN1,STS1
500    CONTINUE
c      calculate the plasiticity
       WRITE(9,*) 'EXTRA CALCULATION'
       STSP=STRS(1325)-STRS(1315)
       STNP=(TH(1315)-TH(1336))/TH(1315)
       P=STSP/STNP
       DENS=(140000)/((3.14156*9.2*9.2/4)*TH(1315))
       WRITE(9,'F4.1') 1315/5
       WRITE(9,'F6.4') STRS(1315)
       WRITE(9,'F8.6') DENS
       WRITE(9,'F8.6') TH(1315)
       WRITE(9,'F12.6,1X,F12.6') P,E1C
       WRITE(9,'F8.5,1X,F8.5') STN1,STS1
       CLOSE(UNIT=9)
       STOP
       END
```

APPENDIX II

Five elements properties
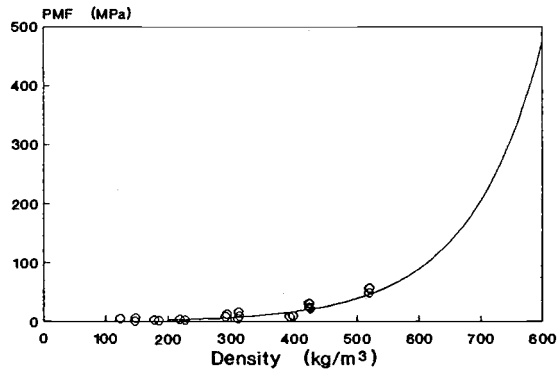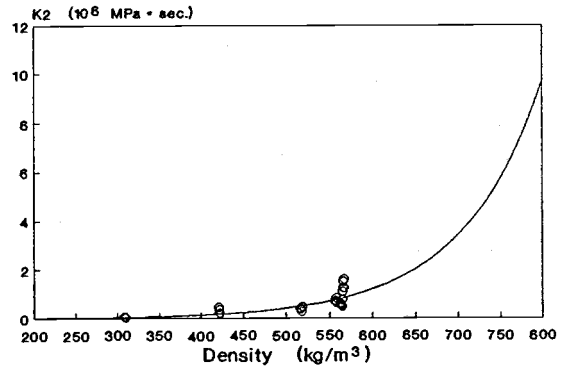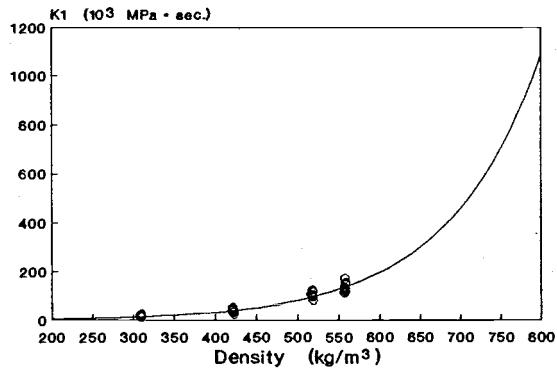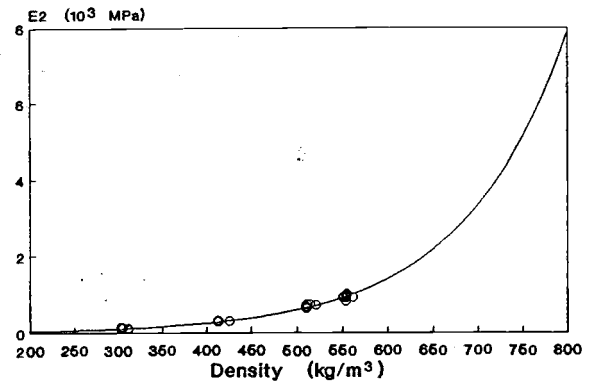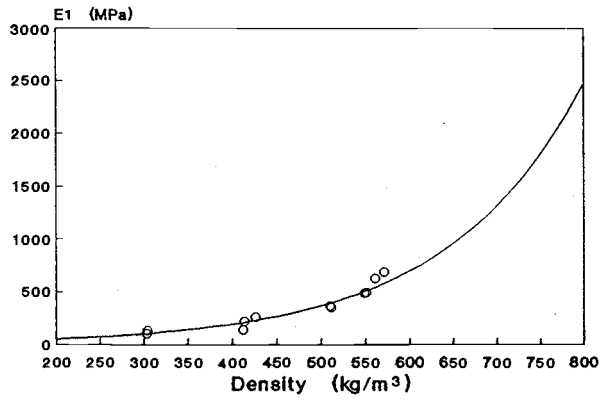
Element properties on T = 25 °C, MC = 0%.
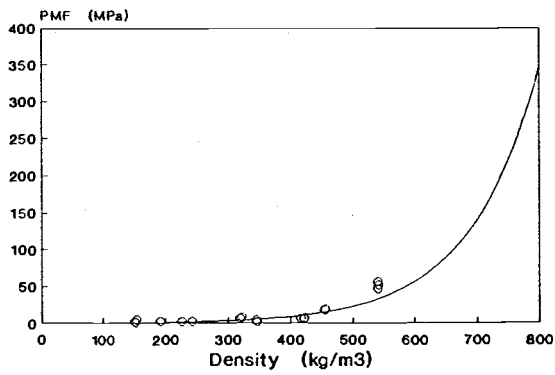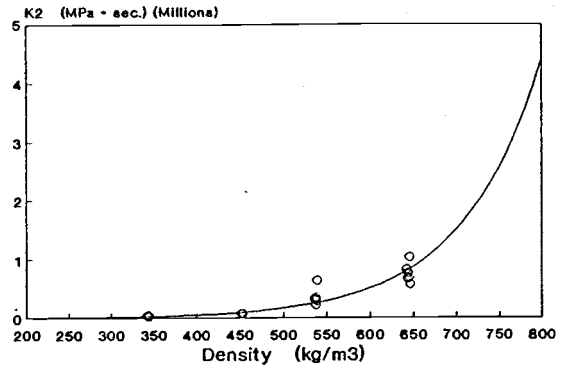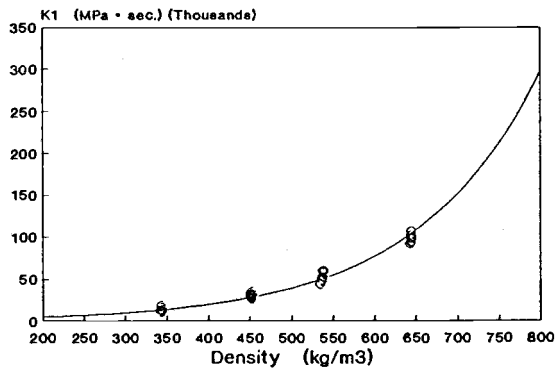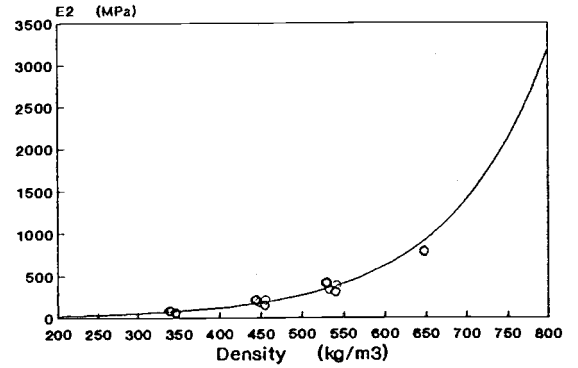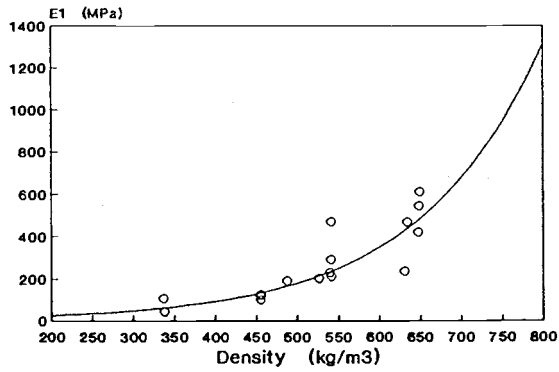
Element properties on T = 25 °C, MC = 4%.
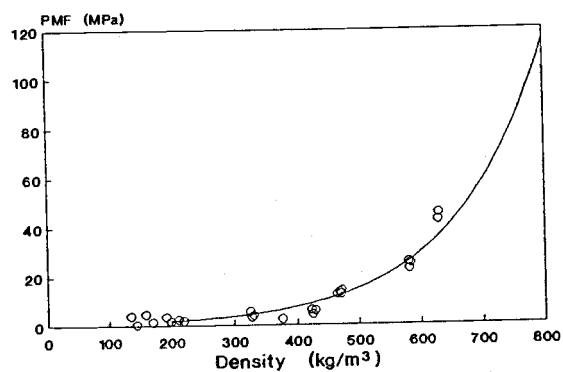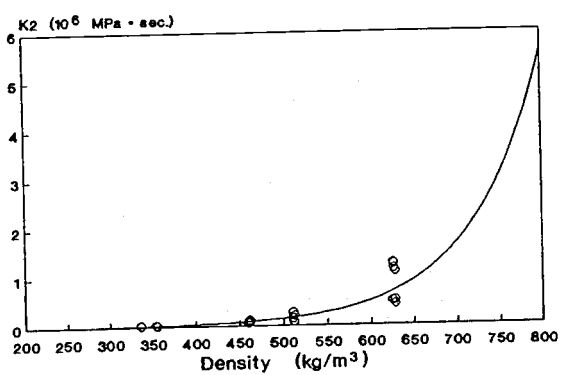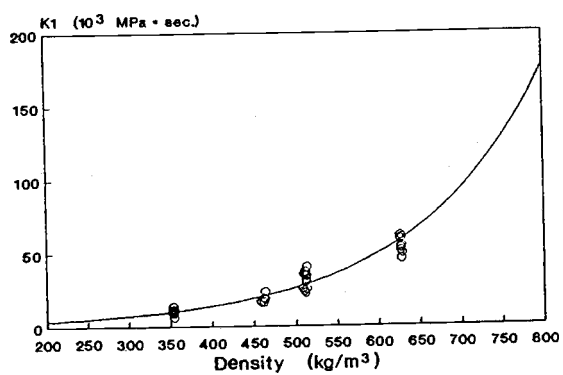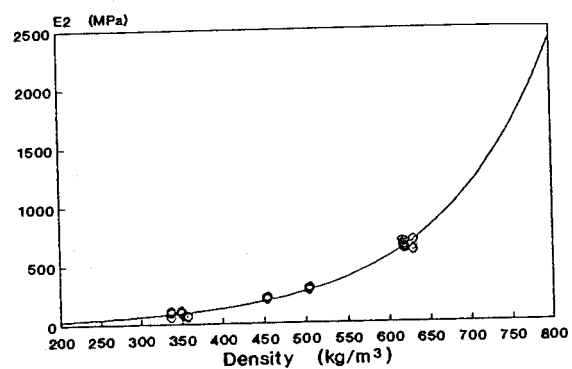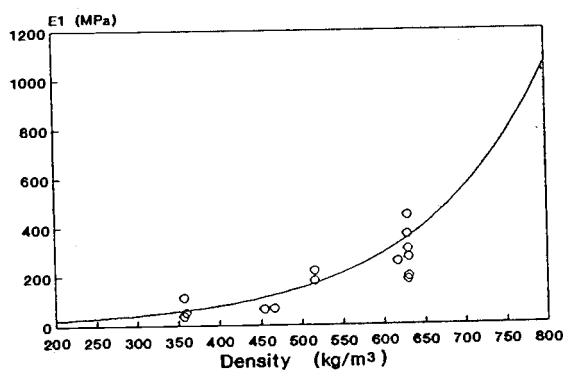
Element properties on T = 25 °C, MC = 10%.
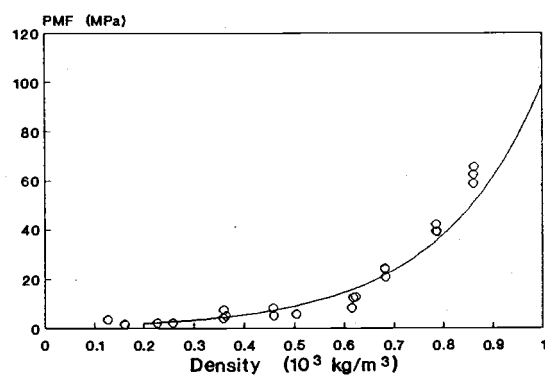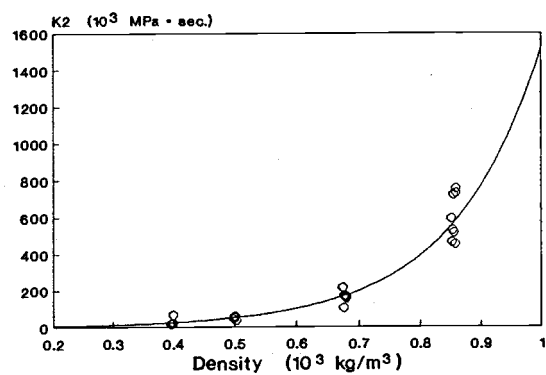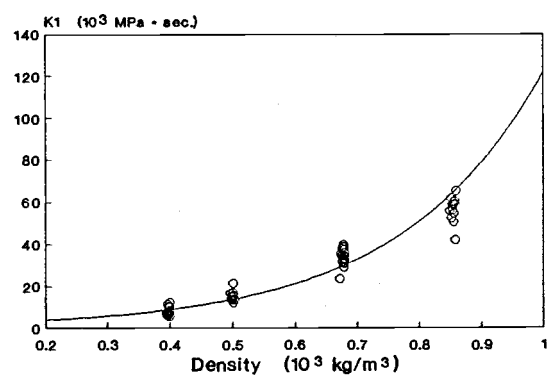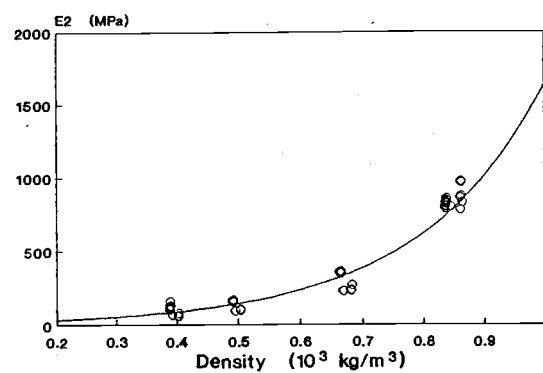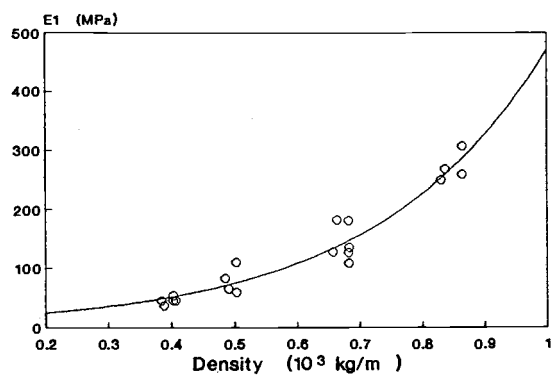
Element properties on T = 25 °C, MC = 16%.
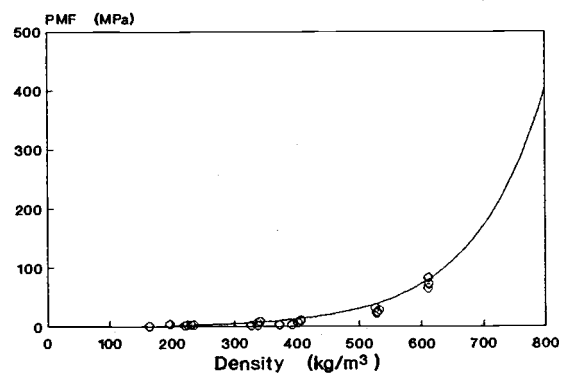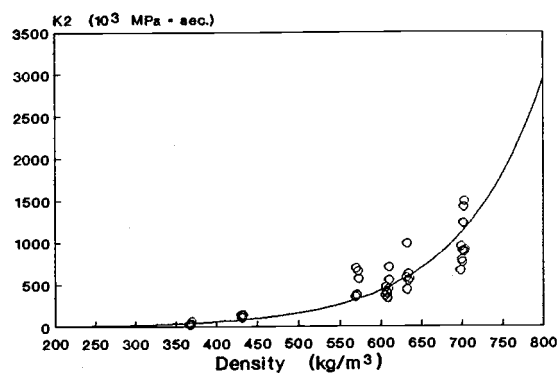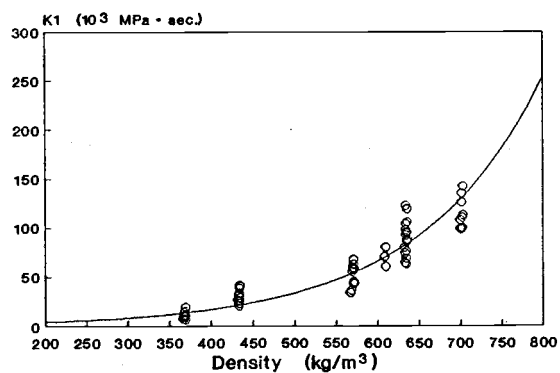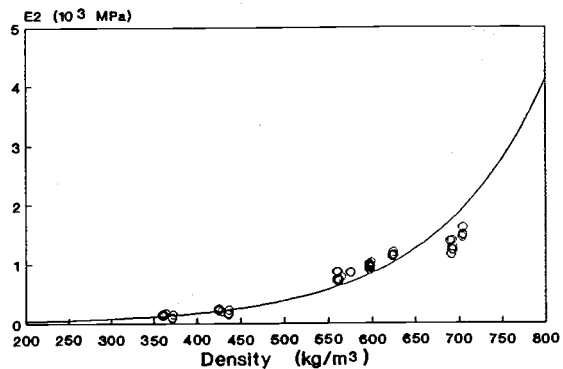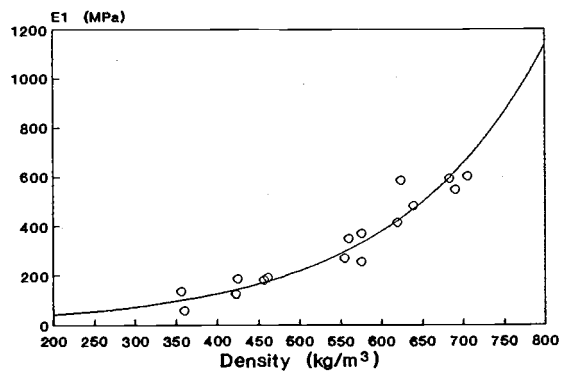
Element properties on T = 100 °C, MC = 0%.
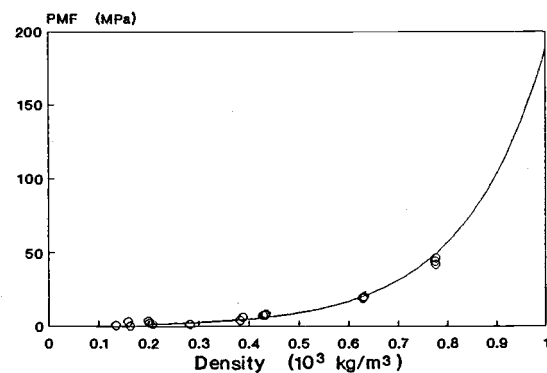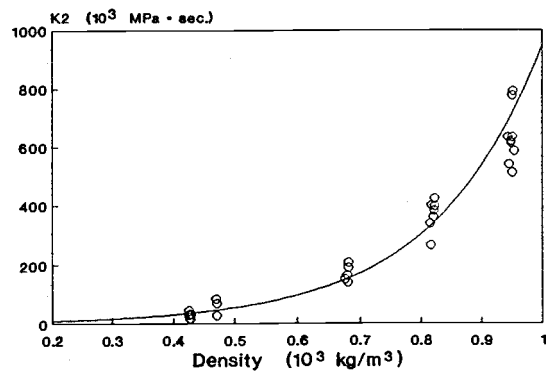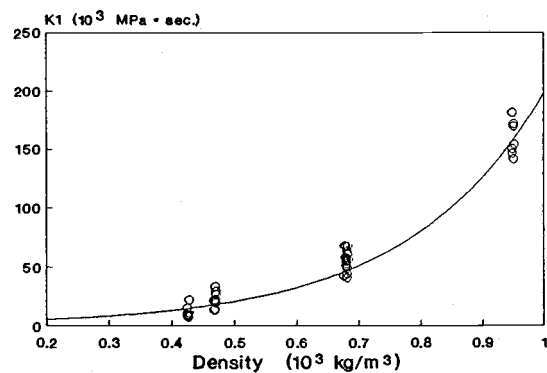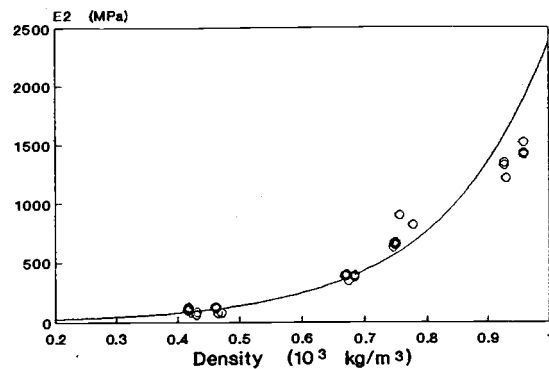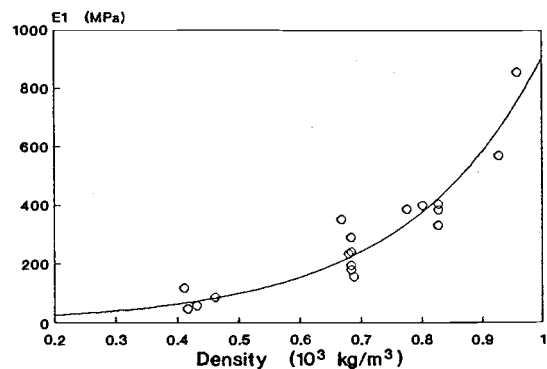
Element properties on T = 100 °C, MC = 4%.
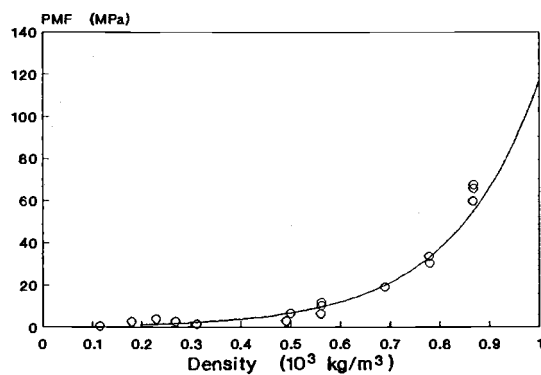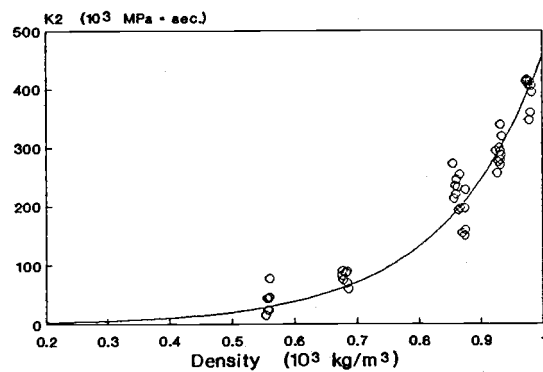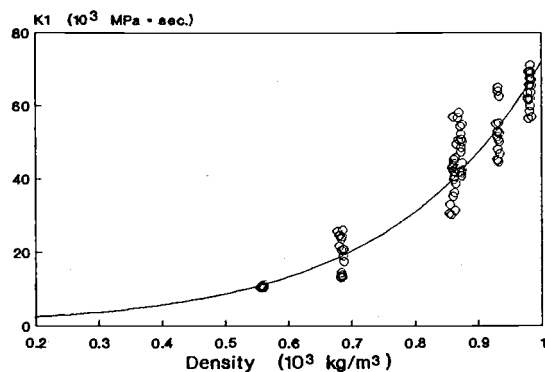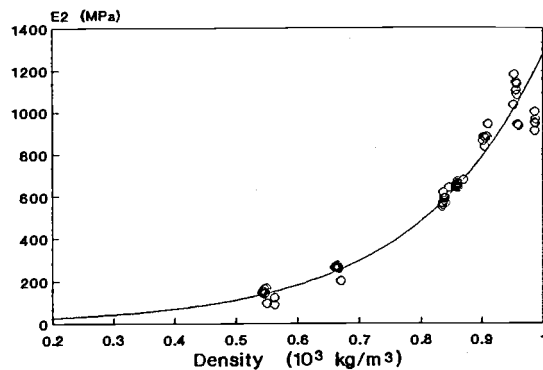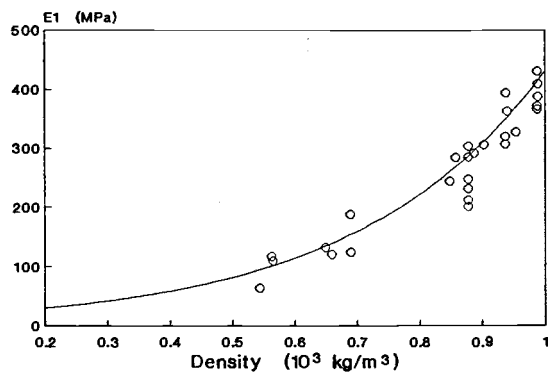
Element properties on T = 100 °C, MC = 10%.
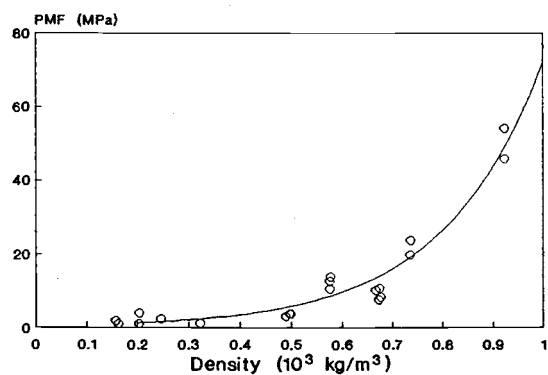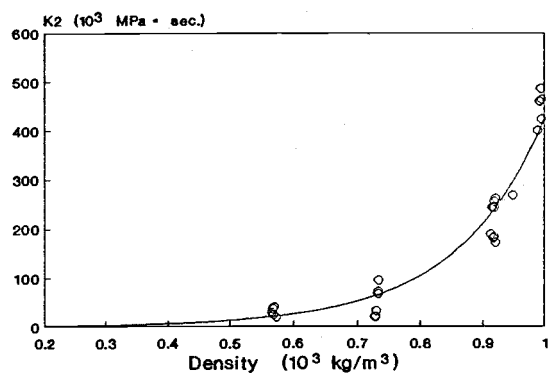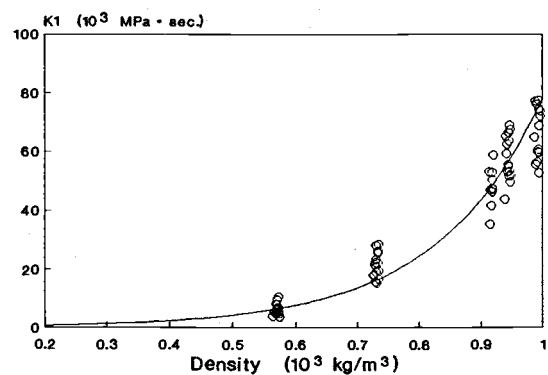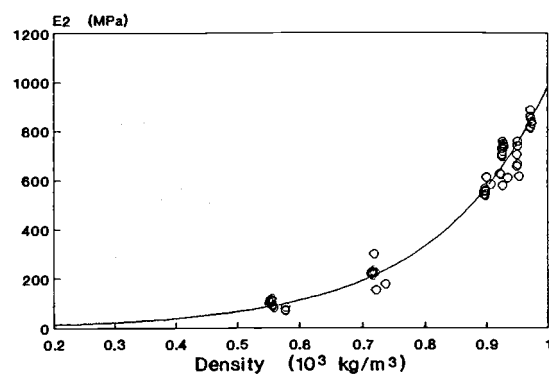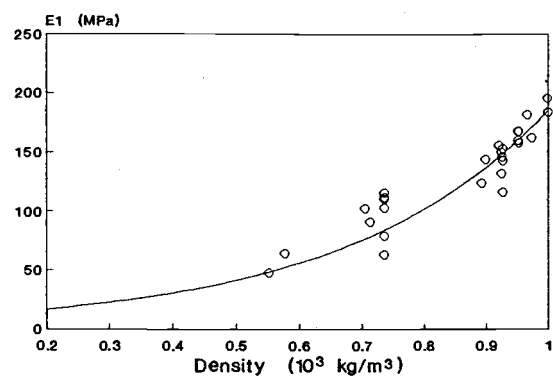
Element properties on T = 100 ºC, MC = 16%.
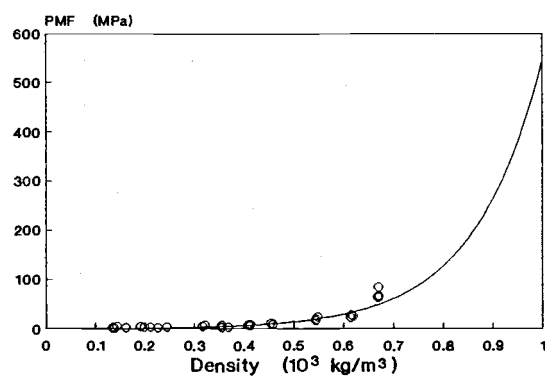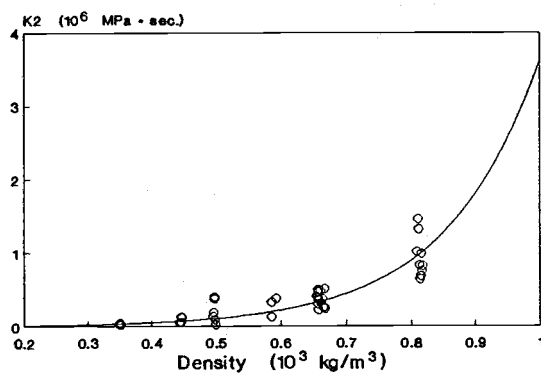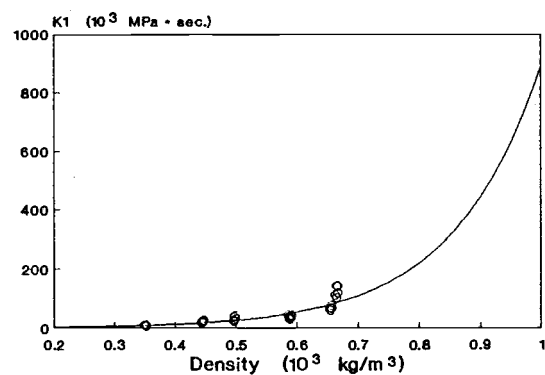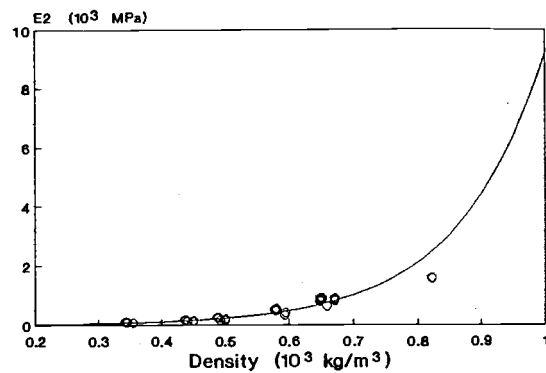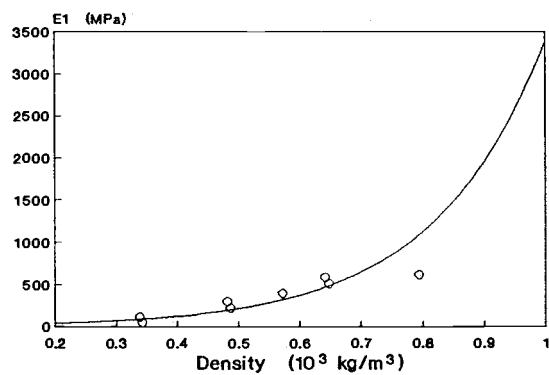
Element properties on T = 120 °C, MC = 0%.
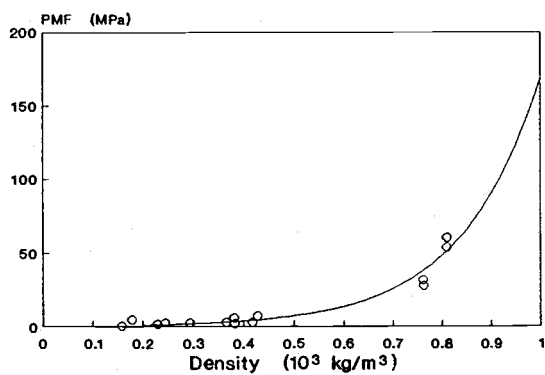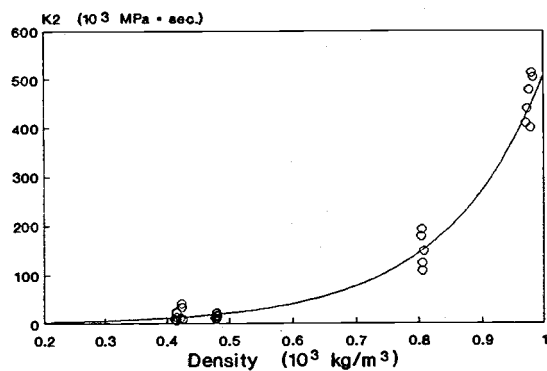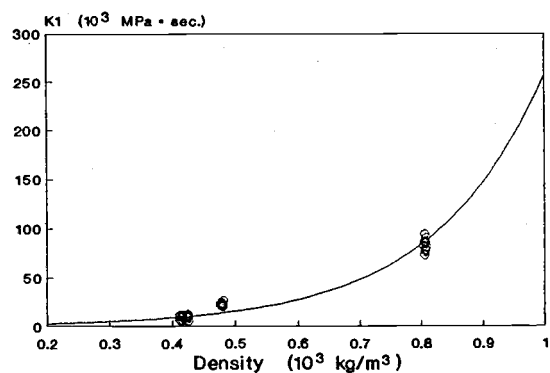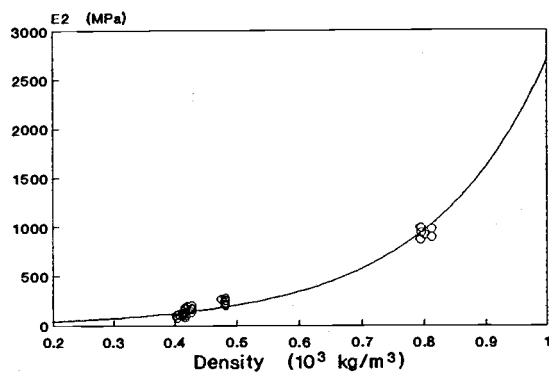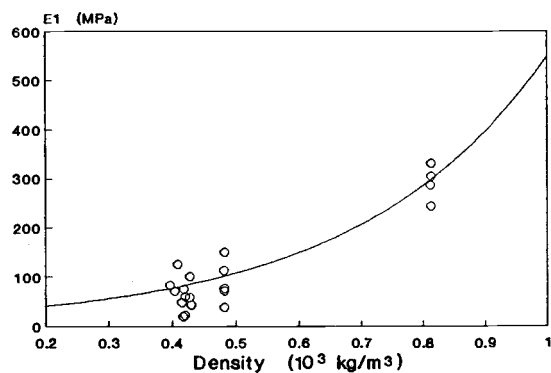
Element properties on T = 120 °C, MC = 4%.
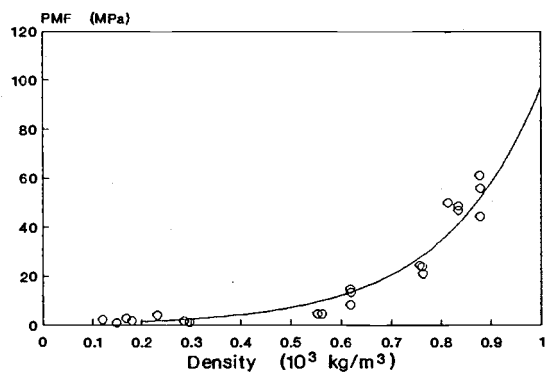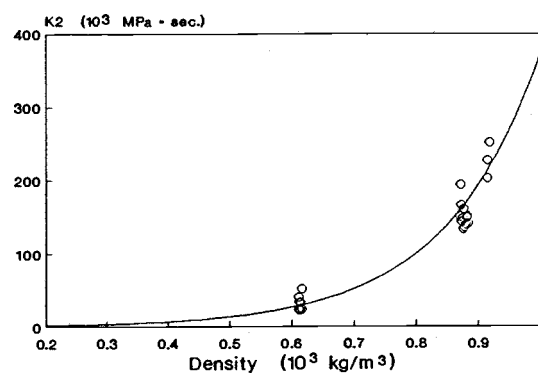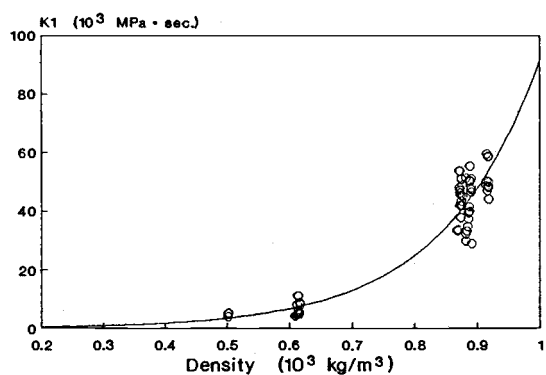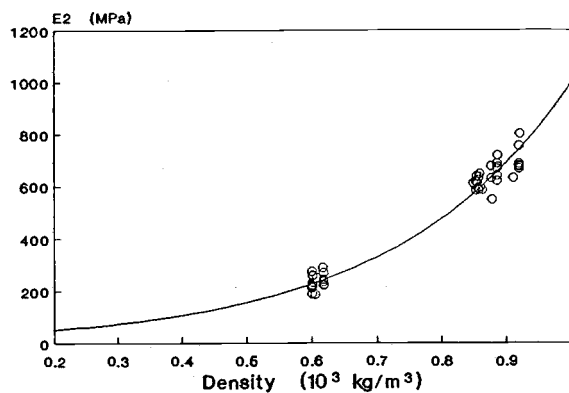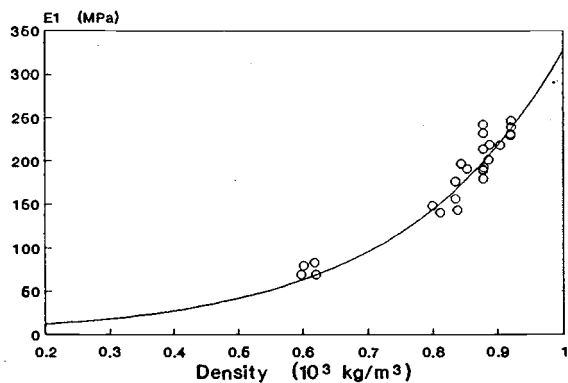
Element properties on T = 120 °C, MC = 10%.
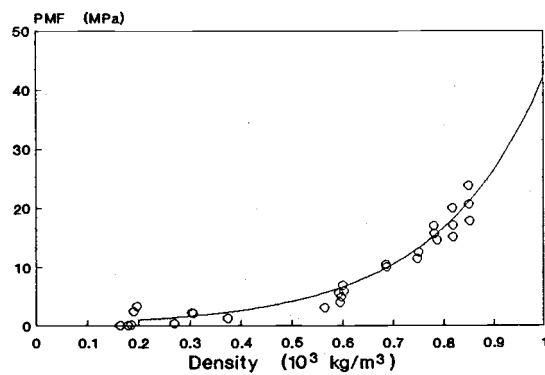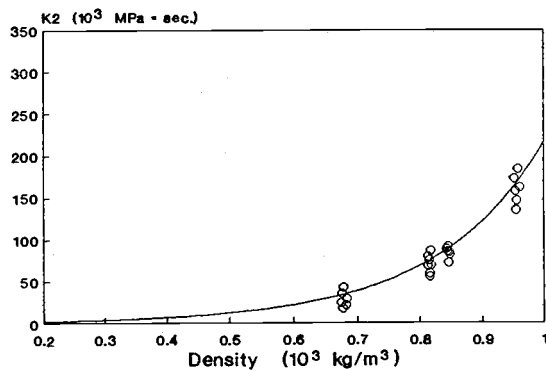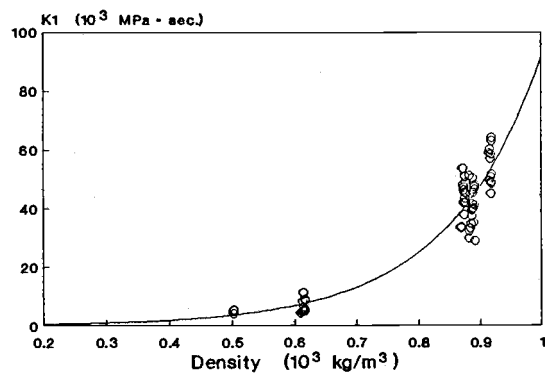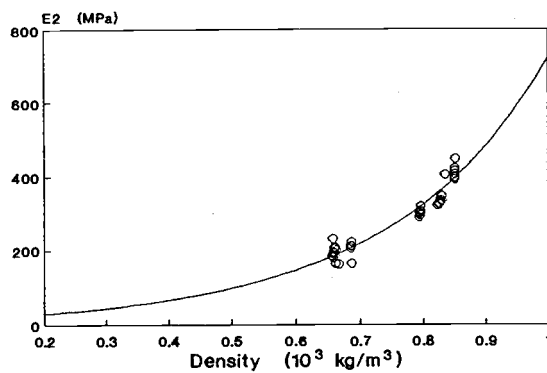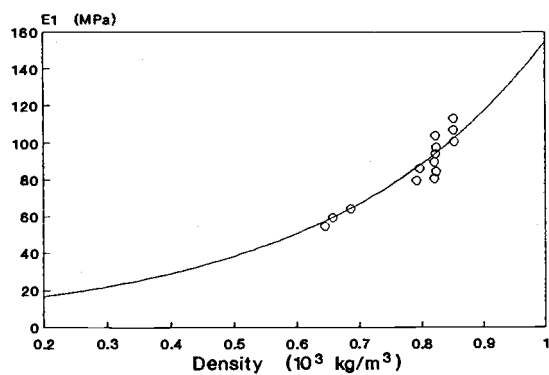
Element properties on T = 120 °C, MC = 16%.
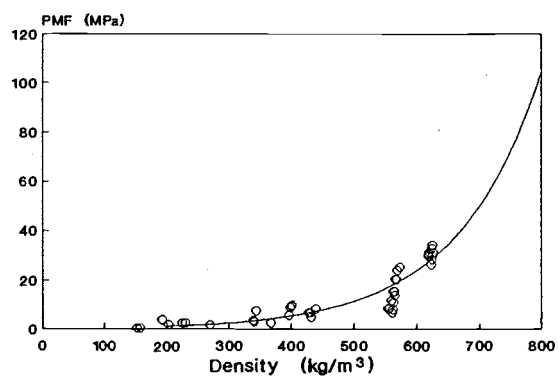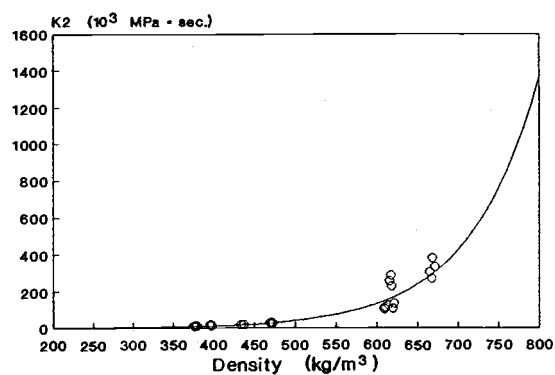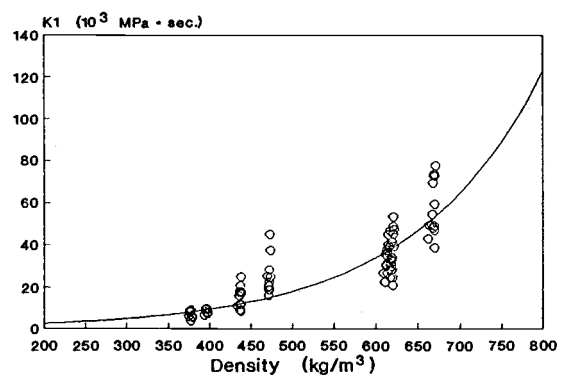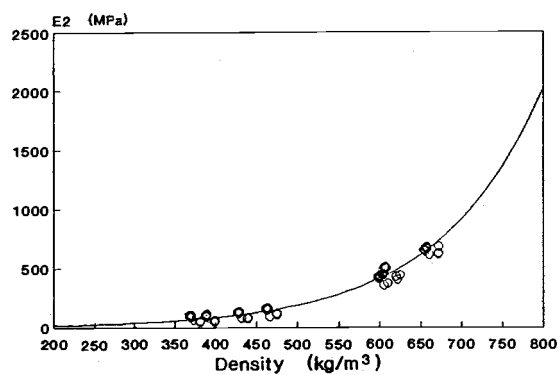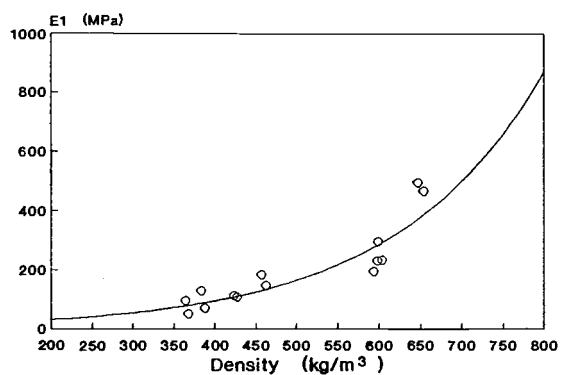
Element properties on T = 150 °C, MC = 0%.
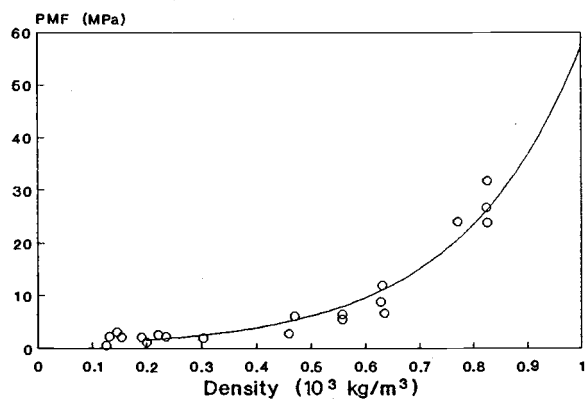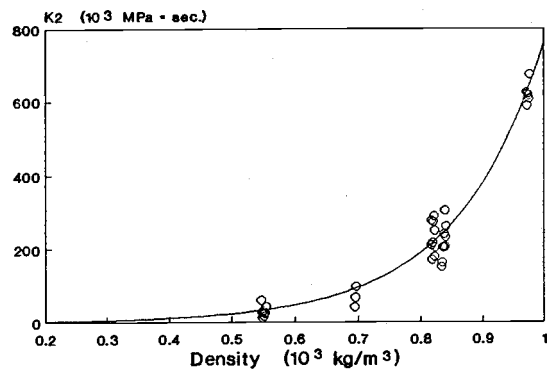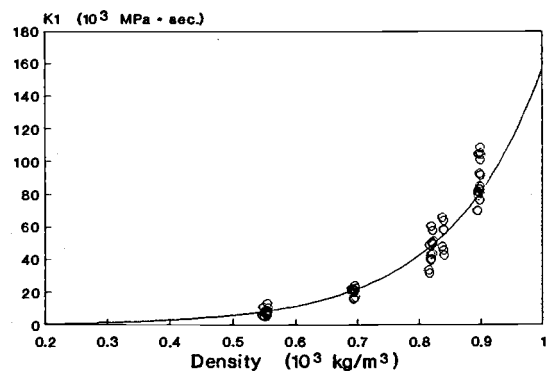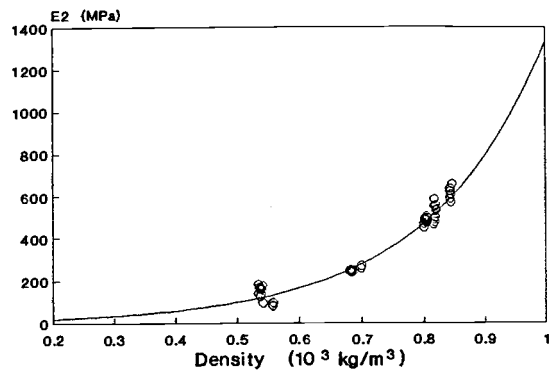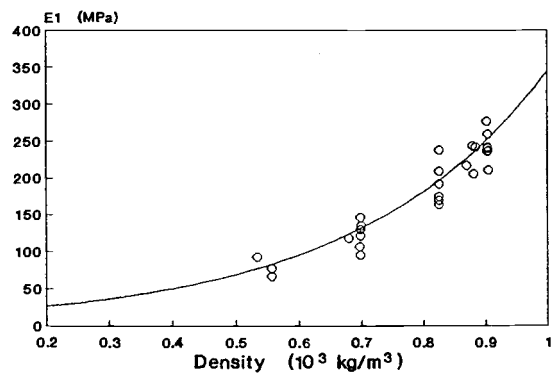
Element properties on T = 150 °C, MC = 4%.
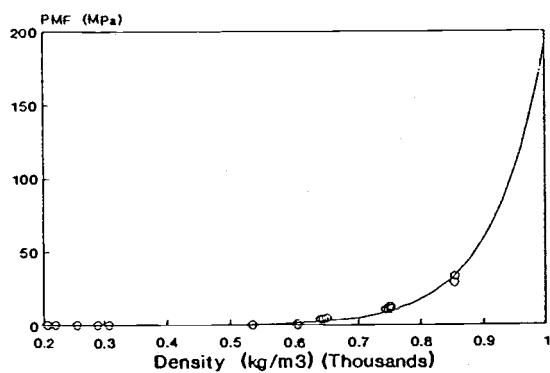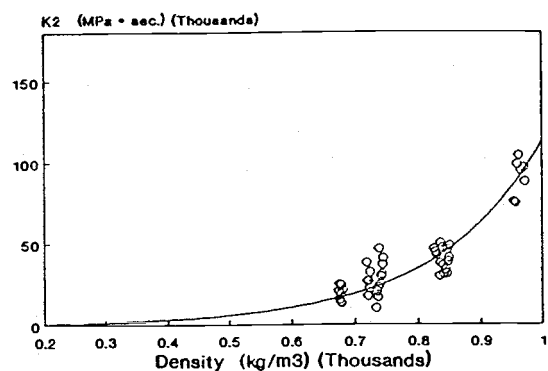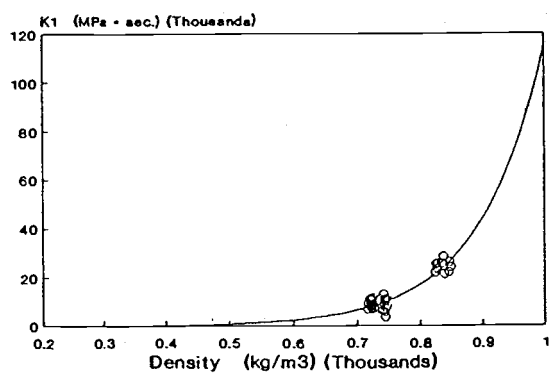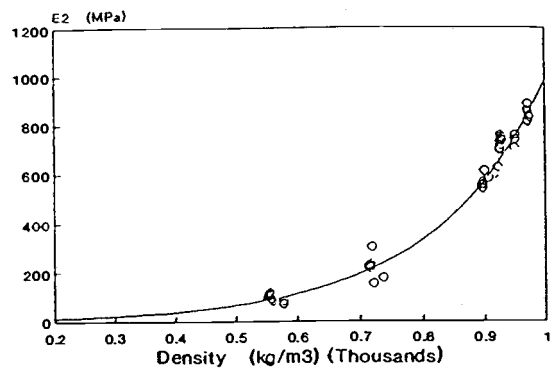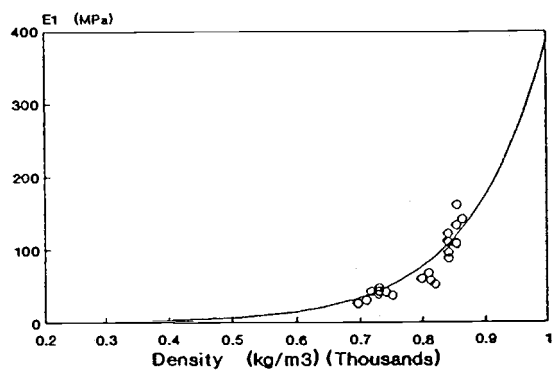
Element properties on T = 150 °C, MC = 10 %.
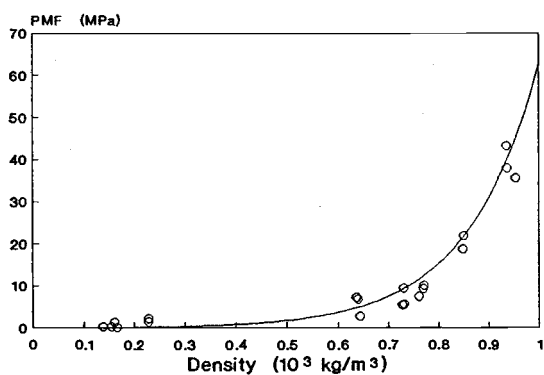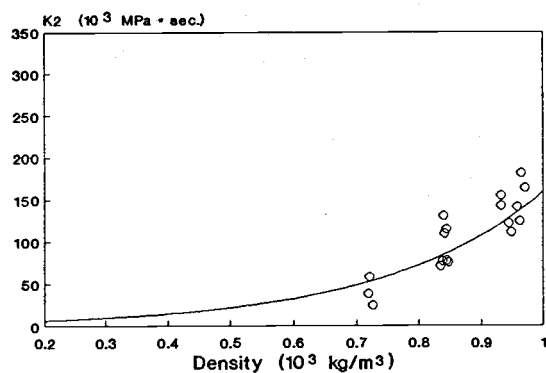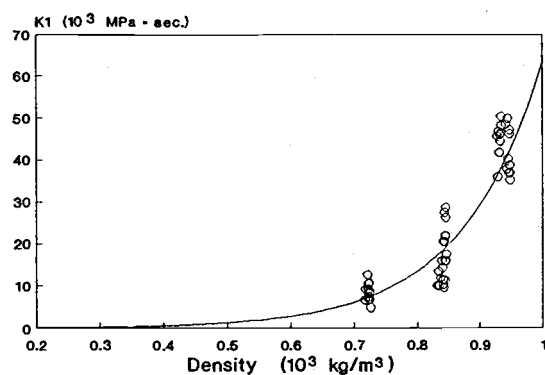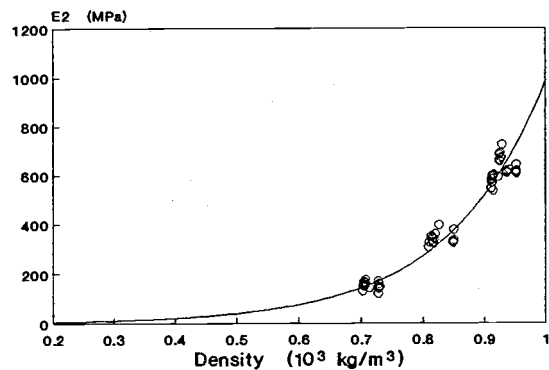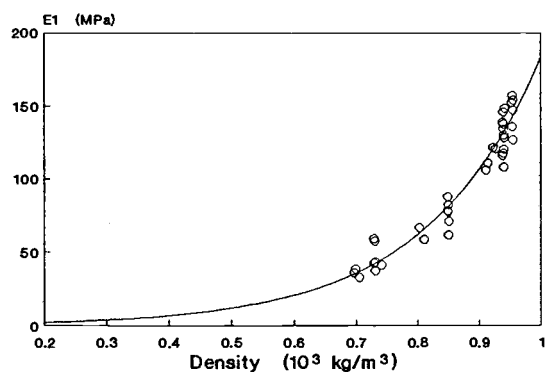
Element properties on T = 150 °C, MC = 16%.

APPENDIX III

Regression results

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: E1250   Independent variable: del250

                              Standard   T   Prob.
Parameter   Estimate   Error   Value   Level

Intercept   2.72063   0.277983   9.78704   .00000
Slope   6.36424E-3   5.86637E-4   10.8487   .00000

                        Analysis of Variance

Source   Sum of Squares   Df   Mean Square   F-Ratio   Prob. Level
Model   3.97536   1   3.97536   117.6939   .00000
Error   .3039937   9   .0337771

Total (Corr.)   4.2793507   10

Correlation Coefficient = 0.963827   R-squared = 92.90 percent
Stnd. Error of Est. = 0.183785

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: E1254   Independent variable: del254

                              Standard   T   Prob.
Parameter   Estimate   Error   Value   Level

Intercept   1.88442   0.430679   4.37546   .00054
Slope   6.62003E-3   8.10843E-4   8.16437   .00000

                        Analysis of Variance

Source   Sum of Squares   Df   Mean Square   F-Ratio   Prob. Level
Model   7.043969   1   7.043969   66.65693   .00000
Error   1.585125   15   .105675

Total (Corr.)   8.629094   16

Correlation Coefficient = 0.903496   R-squared = 81.63 percent
Stnd. Error of Est. = 0.325077

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: E12510   Independent variable: del2510

                              Standard   T   Prob.
Parameter   Estimate   Error   Value   Level

Intercept   1.79215   0.394418   4.54378   .00067
Slope   6.47299E-3   7.29727E-4   8.87042   .00000

                        Analysis of Variance

Source   Sum of Squares   Df   Mean Square   F-Ratio   Prob. Level
Model   6.972136   1   6.972136   78.68437   .00000
Error   1.063307   12   .088609

Total (Corr.)   8.035443   13

Correlation Coefficient = 0.93149   R-squared = 86.77 percent
Stnd. Error of Est. = 0.297672

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: E12516   Independent variable: del2516

                              Standard   T   Prob.
Parameter   Estimate   Error   Value   Level

Intercept   2.47814   0.196622   12.6036   .00000
Slope   3.67729E-3   3.1394E-4   11.7134   .00000

                        Analysis of Variance

Source   Sum of Squares   Df   Mean Square   F-Ratio   Prob. Level
Model   7.29773   1   7.29773   137.2027   .00000
Error   .957410   18   .053189

Total (Corr.)   8.255143   19

Correlation Coefficient = 0.940225   R-squared = 88.40 percent
Stnd. Error of Est. = 0.230628

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: P25   Independent variable: dnp25

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	-0.50492	0.322201	-1.5671	.13136
Slope	8.3318E-3	9.18032E-4	9.07572	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	24.062700	1	24.062700	82.36865	.00000
Error	6.426953	22	.292134		
Total (Corr.)	30.489653	23			

Correlation Coefficient = 0.888374   R-squared = 78.92 percent
Stnd. Error of Est. = 0.540494

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: P254   Independent variable: dnp254

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	-1.37294	0.412225	-3.33055	.00372
Slope	9.03376E-3	1.10158E-3	8.20074	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	26.800684	1	26.800684	67.25211	.00000
Error	7.173192	18	.398511		
Total (Corr.)	33.973876	19			

Correlation Coefficient = 0.888179   R-squared = 78.89 percent
Stnd. Error of Est. = 0.631277

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: P2510   Independent variable: dnp2510

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	-0.715827	0.304929	-2.34752	.02748
Slope	6.83013E-3	7.43402E-4	9.18767	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	29.748193	1	29.748193	84.41323	.00000
Error	8.457876	24	.352412		
Total (Corr.)	38.206070	25			

Correlation Coefficient = 0.882397   R-squared = 77.86 percent
Stnd. Error of Est. = 0.593643

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: P2516   Independent variable: dnp2516

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	-0.20318	0.172393	-1.17858	.25175
Slope	4.80322E-3	2.95054E-4	16.2791	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	30.35691	1	30.35691	265.0097	.00000
Error	2.405554	21	.114550		
Total (Corr.)	32.762466	22			

Correlation Coefficient = 0.962588   R-squared = 92.66 percent
Stnd. Error of Est. = 0.338453

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K1250   Independent variable: dnk1250

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	7.03929	0.125363	56.1511	.00000
Slope	8.5716E-3	2.69966E-4	31.7506	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	38.2613	1	38.2613	1008.103	.00000
Error	1.897690	50	.037954		
Total (Corr.)	40.159037	51			

Correlation Coefficient = 0.976087   R-squared = 95.27 percent
Stnd. Error of Est. = 0.194817

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K1254   Independent variable: dnk1254

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	7.2095	0.0800122	90.1051	.00000
Slope	6.74147E-3	1.58251E-4	42.5999	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	25.3121	1	25.3121	1814.750	.00000
Error	.739242	53	.013948		
Total (Corr.)	26.051322	54			

Correlation Coefficient = 0.98571   R-squared = 97.16 percent
Stnd. Error of Est. = 0.118102

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K12510   Independent variable: dnk12510

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	6.99715	0.150285	46.5592	.00000
Slope	6.35302E-3	3.07489E-4	20.6609	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	15.28876	1	15.28876	426.8742	.00000
Error	1.396809	39	.035816		
Total (Corr.)	16.685569	40			

Correlation Coefficient = 0.957229   R-squared = 91.63 percent
Stnd. Error of Est. = 0.18925

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K12516   Independent variable: dnk12516

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	7.3551	0.0859624	85.5618	.00000
Slope	4.35375E-3	1.37715E-4	31.6141	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	36.88287	1	36.88287	999.4514	.00000
Error	2.583218	70	.036903		
Total (Corr.)	39.466093	71			

Correlation Coefficient = 0.966719   R-squared = 93.45 percent
Stnd. Error of Est. = 0.192102

```
Regression Analysis - Exponential model: Y = exp(a+bX)
-----------------------------------------------------------------------
Dependent variable: E2250                    Independent variable: dne2250
-----------------------------------------------------------------------
                         Standard          T          Prob.
Parameter      Estimate    Error         Value        Level
-----------------------------------------------------------------------
Intercept      2.09391     0.074518      28.0994      .00000
Slope          8.59909E-3  1.60754E-4    53.4921      .00000
-----------------------------------------------------------------------

                    Analysis of Variance
-----------------------------------------------------------------------
Source          Sum of Squares   Df  Mean Square   F-Ratio   Prob. Level
Model                51.0094      1     51.0094    2861.408       .00000
Error                1.194386    67     .017827
-----------------------------------------------------------------------
Total (Corr.)        52.203750   68

Correlation Coefficient = 0.988494       R-squared =  97.71 percent
Stnd. Error of Est. = 0.133517
```

```
Regression Analysis - Exponential model: Y = exp(a+bX)
-----------------------------------------------------------------------
Dependent variable: E2254                    Independent variable: dne2254
-----------------------------------------------------------------------
                         Standard          T          Prob.
Parameter      Estimate    Error         Value        Level
-----------------------------------------------------------------------
Intercept      1.50248     0.130198      11.54        .00000
Slope          8.20522E-3  2.7849E-4     29.4633      .00000
-----------------------------------------------------------------------

                    Analysis of Variance
-----------------------------------------------------------------------
Source          Sum of Squares   Df  Mean Square   F-Ratio   Prob. Level
Model                35.69034     1     35.69034   868.0868       .00000
Error                2.343486    57     .041114
-----------------------------------------------------------------------
Total (Corr.)        38.033822   58

Correlation Coefficient = 0.968702       R-squared =  93.84 percent
Stnd. Error of Est. = 0.202765
```

```
Regression Analysis - Exponential model: Y = exp(a+bX)
-----------------------------------------------------------------------
Dependent variable: E22510                   Independent variable: dne22510
-----------------------------------------------------------------------
                         Standard          T          Prob.
Parameter      Estimate    Error         Value        Level
-----------------------------------------------------------------------
Intercept      1.94875     0.100181      19.4523      .00000
Slope          7.29642E-3  2.12318E-4    34.3655      .00000
-----------------------------------------------------------------------

                    Analysis of Variance
-----------------------------------------------------------------------
Source          Sum of Squares   Df  Mean Square   F-Ratio   Prob. Level
Model                47.4078      1     47.4078    1180.989       .00000
Error                2.729689    68     .040142
-----------------------------------------------------------------------
Total (Corr.)        50.137526   69

Correlation Coefficient = 0.972397       R-squared =  94.56 percent
Stnd. Error of Est. = 0.200356
```

```
Regression Analysis - Exponential model: Y = exp(a+bX)
-----------------------------------------------------------------------
Dependent variable: E22516                   Independent variable: dne22516
-----------------------------------------------------------------------
                         Standard          T          Prob.
Parameter      Estimate    Error         Value        Level
-----------------------------------------------------------------------
Intercept      2.56073     0.116276      22.0228      .00000
Slope          4.83953E-3  1.86035E-4    26.0141      .00000
-----------------------------------------------------------------------

                    Analysis of Variance
-----------------------------------------------------------------------
Source          Sum of Squares   Df  Mean Square   F-Ratio   Prob. Level
Model                50.21551     1     50.21551   676.7322       .00000
Error                5.194205    70     .074203
-----------------------------------------------------------------------
Total (Corr.)        55.409719   71

Correlation Coefficient = 0.951976       R-squared =  90.63 percent
Stnd. Error of Est. = 0.272402
```

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K2250   Independent variable: dnk2250

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	7.71583	0.365215	21.1268	.00000
Slope	0.0104692	7.2948E-4	14.3516	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	29.07047	1	29.07047	205.9692	.00000
Error	3.810778	27	.141140		
Total (Corr.)	32.881250	28			

Correlation Coefficient = 0.940268   R-squared = 88.41 percent
Stnd. Error of Est. = 0.375686

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K2254   Independent variable: dnk2254

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	6.67971	0.252709	26.4324	.00000
Slope	0.0107715	4.96976E-4	21.674	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	44.47599	1	44.47599	469.7622	.00000
Error	2.556297	27	.094678		
Total (Corr.)	47.032289	28			

Correlation Coefficient = 0.972444   R-squared = 94.56 percent
Stnd. Error of Est. = 0.307697

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K22510   Independent variable: dnk2510

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	5.89205	0.289344	20.3635	.00000
Slope	0.0120526	6.23932E-4	19.3171	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	59.57899	1	59.57899	373.1506	.00000
Error	4.789942	30	.159665		
Total (Corr.)	64.368931	31			

Correlation Coefficient = 0.962074   R-squared = 92.56 percent
Stnd. Error of Est. = 0.399581

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K22516   Independent variable: dnk22516

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	7.48219	0.236305	31.6633	.00000
Slope	6.74908E-3	3.65764E-4	18.452	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	40.91912	1	40.91912	340.4763	.00000
Error	3.244914	27	.120182		
Total (Corr.)	44.164031	28			

Correlation Coefficient = 0.962562   R-squared = 92.65 percent
Stnd. Error of Est. = 0.346673

Regression Analysis - Exponential model: Y = exp(a+bX)
```
--------------------------------------------------------------------------
Dependent variable: E11000                    Independent variable: del1000
--------------------------------------------------------------------------
                          Standard          T          Prob.
Parameter     Estimate      Error         Value        Level
--------------------------------------------------------------------------
Intercept     2.65174      0.277593       9.55262       .00000
Slope         5.479E-3     5.00077E-4    10.9563        .00000
--------------------------------------------------------------------------

                     Analysis of Variance
--------------------------------------------------------------------------
Source       Sum of Squares   Df   Mean Square   F-Ratio   Prob. Level
Model             6.08540      1      6.08540    120.0407      .00000
Error              .709723    14       .050695
--------------------------------------------------------------------------
Total (Corr.)     6.795125    15

Correlation Coefficient = 0.946337        R-squared =  89.56 percent
Stnd. Error of Est. = 0.225154
```

Regression Analysis - Exponential model: Y = exp(a+bX)
```
--------------------------------------------------------------------------
Dependent variable: E11004                    Independent variable: del1004
--------------------------------------------------------------------------
                          Standard          T          Prob.
Parameter     Estimate      Error         Value        Level
--------------------------------------------------------------------------
Intercept     2.39771      0.243719       9.83799       .00000
Slope         4.41083E-3   3.41455E-4    12.9178        .00000
--------------------------------------------------------------------------

                     Analysis of Variance
--------------------------------------------------------------------------
Source       Sum of Squares   Df   Mean Square   F-Ratio   Prob. Level
Model            11.69207      1     11.69207    166.8687      .00000
Error             1.261215    18       .070067
--------------------------------------------------------------------------
Total (Corr.)    12.953287    19

Correlation Coefficient = 0.95007         R-squared =  90.26 percent
Stnd. Error of Est. = 0.264703
```

Regression Analysis - Exponential model: Y = exp(a+bX)
```
--------------------------------------------------------------------------
Dependent variable: E110010                   Independent variable: de110010
--------------------------------------------------------------------------
                          Standard          T          Prob.
Parameter     Estimate      Error         Value        Level
--------------------------------------------------------------------------
Intercept     2.73551      0.461197       5.93133       .00001
Slope         3.33078E-3   5.57662E-4     5.97276       .00001
--------------------------------------------------------------------------

                     Analysis of Variance
--------------------------------------------------------------------------
Source       Sum of Squares   Df   Mean Square   F-Ratio   Prob. Level
Model             5.452407     1      5.452407    35.67392     .00001
Error             2.903963    19       .152840
--------------------------------------------------------------------------
Total (Corr.)     8.356371    20

Correlation Coefficient = 0.807766        R-squared =  65.25 percent
Stnd. Error of Est. = 0.390948
```

Regression Analysis - Exponential model: Y = exp(a+bX)
```
--------------------------------------------------------------------------
Dependent variable: E110016                   Independent variable: de110016
--------------------------------------------------------------------------
                          Standard          T          Prob.
Parameter     Estimate      Error         Value        Level
--------------------------------------------------------------------------
Intercept     2.22265      0.263393       8.43853       .00000
Slope         2.99797E-3   3.11289E-4     9.63083       .00000
--------------------------------------------------------------------------

                     Analysis of Variance
--------------------------------------------------------------------------
Source       Sum of Squares   Df   Mean Square   F-Ratio   Prob. Level
Model             3.944767     1      3.944767    92.75284     .00000
Error              .723008    17       .042530
--------------------------------------------------------------------------
Total (Corr.)     4.667775    18

Correlation Coefficient = 0.919297        R-squared =  84.51 percent
Stnd. Error of Est. = 0.206228
```

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: P1000   Independent variable: dnpl000

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	-1.45454	0.389264	-3.73665	.00102
Slope	8.57181E-3	9.12743E-4	9.39126	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	38.746038	1	38.746038	88.19582	.00000
Error	10.543640	24	.439318		
Total (Corr.)	49.289678	25			

Correlation Coefficient = 0.886616   R-squared = 78.61 percent
Stnd. Error of Est. = 0.662811

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: P1004   Independent variable: dnpl004

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	-0.736199	0.280678	-2.62293	.01725
Slope	5.97381E-3	5.79341E-4	10.3114	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	33.22947	1	33.22947	106.3245	.00000
Error	5.625519	18	.312529		
Total (Corr.)	38.854985	19			

Correlation Coefficient = 0.92478   R-squared = 85.52 percent
Stnd. Error of Est. = 0.559043

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: P10010   Independent variable: dnpl0010

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	-0.942334	0.303597	-3.10389	.00777
Slope	5.70627E-3	5.11295E-4	11.1604	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	32.51344	1	32.51344	124.5552	.00000
Error	3.654509	14	.261036		
Total (Corr.)	36.167945	15			

Correlation Coefficient = 0.948134   R-squared = 89.90 percent
Stnd. Error of Est. = 0.510917

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: P10016   Independent variable: dnpl0016

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	-0.728678	0.276844	-2.63209	.01642
Slope	5.0081E-3	4.74661E-4	10.5509	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	28.44971	1	28.44971	111.3213	.00000
Error	4.855713	19	.255564		
Total (Corr.)	33.305421	20			

Correlation Coefficient = 0.924233   R-squared = 85.42 percent
Stnd. Error of Est. = 0.505533

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K11000   Independent variable: dnk11000

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	7.05826	0.19028	37.0941	.00000
Slope	6.73133E-3	3.33237E-4	20.1998	.00000

                        Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	46.64891	1	46.64891	408.0320	.00000
Error	8.688823	76	.114327		
Total (Corr.)	55.337736	77			

Correlation Coefficient = 0.918142   R-squared = 84.30 percent
Stnd. Error of Est. = 0.338122

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K11004   Independent variable: dnk11004

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	7.69316	0.182474	42.1602	.00000
Slope	4.50446E-3	2.88447E-4	15.6162	.00000

                        Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	30.80655	1	30.80655	243.8672	.00000
Error	5.810954	46	.126325		
Total (Corr.)	36.617499	47			

Correlation Coefficient = 0.917228   R-squared = 84.13 percent
Stnd. Error of Est. = 0.355422

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K110010   Independent variable: dnk110010

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	6.97595	0.140979	49.4821	.00000
Slope	4.20846E-3	1.64857E-4	25.528	.00000

                        Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	32.90959	1	32.90959	651.6771	.00000
Error	5.25198	104	.05050		
Total (Corr.)	38.16157	105			

Correlation Coefficient = 0.928642   R-squared = 86.24 percent
Stnd. Error of Est. = 0.224722

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K110016   Independent variable: dnk110016

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	5.4637	0.128274	42.5941	.00000
Slope	5.80376E-3	1.57136E-4	36.9346	.00000

                        Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	77.6756	1	77.6756	1364.164	.00000
Error	4.555206	80	.056940		
Total (Corr.)	82.230823	81			

Correlation Coefficient = 0.971908   R-squared = 94.46 percent
Stnd. Error of Est. = 0.238621

```
Regression Analysis - Exponential model: Y = exp(a+bX)
----------------------------------------------------------------------------
Dependent variable: E21000                    Independent variable: dne21000
----------------------------------------------------------------------------
                              Standard           T          Prob.
Parameter      Estimate        Error           Value        Level
----------------------------------------------------------------------------
Intercept      2.0031        0.109849          18.235       .00000
Slope          7.89901E-3    2.06269E-4        38.2947      .00000
----------------------------------------------------------------------------

                          Analysis of Variance
----------------------------------------------------------------------------
Source           Sum of Squares   Df   Mean Square   F-Ratio    Prob. Level
Model               70.8169        1      70.8169    1466.486      .00000
Error                3.814928     79      .048290
----------------------------------------------------------------------------
Total (Corr.)       74.631838     80

Correlation Coefficient = 0.974106        R-squared =  94.89 percent
Stnd. Error of Est. = 0.21975



Regression Analysis - Exponential model: Y = exp(a+bX)
----------------------------------------------------------------------------
Dependent variable: E21004                    Independent variable: dne21004
----------------------------------------------------------------------------
                              Standard           T          Prob.
Parameter      Estimate        Error           Value        Level
----------------------------------------------------------------------------
Intercept      2.10239       0.096715          21.738       .00000
Slope          5.65738E-3    1.54493E-4        36.6191      .00000
----------------------------------------------------------------------------

                          Analysis of Variance
----------------------------------------------------------------------------
Source           Sum of Squares   Df   Mean Square   F-Ratio    Prob. Level
Model               67.7831        1      67.7831    1340.959      .00000
Error                3.588925     71      .050548
----------------------------------------------------------------------------
Total (Corr.)       71.372027     72

Correlation Coefficient = 0.974533        R-squared =  94.97 percent
Stnd. Error of Est. = 0.224829



Regression Analysis - Exponential model: Y = exp(a+bX)
----------------------------------------------------------------------------
Dependent variable: E210010                   Independent variable: dne210010
----------------------------------------------------------------------------
                              Standard           T          Prob.
Parameter      Estimate        Error           Value        Level
----------------------------------------------------------------------------
Intercept      2.27419       0.0816051         27.8682      .00000
Slope          4.87903E-3    1.01709E-4        47.9706      .00000
----------------------------------------------------------------------------

                          Analysis of Variance
----------------------------------------------------------------------------
Source           Sum of Squares   Df   Mean Square   F-Ratio    Prob. Level
Model               38.9100        1      38.9100    2301.183      .00000
Error                1.183609     70      .016909
----------------------------------------------------------------------------
Total (Corr.)       40.093621     71

Correlation Coefficient = 0.985129        R-squared =  97.05 percent
Stnd. Error of Est. = 0.130033



Regression Analysis - Exponential model: Y = exp(a+bX)
----------------------------------------------------------------------------
Dependent variable: E210016                   Independent variable: dne210016
----------------------------------------------------------------------------
                              Standard           T          Prob.
Parameter      Estimate        Error           Value        Level
----------------------------------------------------------------------------
Intercept      1.47303       0.0908486         16.2141      .00000
Slope          5.41741E-3    1.10598E-4        48.9829      .00000
----------------------------------------------------------------------------

                          Analysis of Variance
----------------------------------------------------------------------------
Source           Sum of Squares   Df   Mean Square   F-Ratio    Prob. Level
Model               56.0551        1      56.0551    2399.320      .00000
Error                1.705493     73      .023363
----------------------------------------------------------------------------
Total (Corr.)       57.760615     74

Correlation Coefficient = 0.985126        R-squared =  97.05 percent
Stnd. Error of Est. = 0.152849
```

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K21000   Independent variable: dnk21000

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	7.14709	0.294248	24.2893	.00000
Slope	9.68855E-3	5.01388E-4	19.3235	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	52.89470	1	52.89470	373.3968	.00000
Error	5.807985	41	.141658		
Total (Corr.)	58.702690	42			

Correlation Coefficient = 0.949242   R-squared = 90.11 percent
Stnd. Error of Est. = 0.376375

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K221004   Independent variable: dnk21004

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	8.06327	0.242736	33.2182	.00000
Slope	5.701E-3	3.33853E-4	17.0764	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	47.76560	1	47.76560	291.6019	.00000
Error	5.077928	31	.163804		
Total (Corr.)	52.843525	32			

Correlation Coefficient = 0.95074   R-squared = 90.39 percent
Stnd. Error of Est. = 0.404727

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K210010   Independent variable: dnk210010

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	6.81938	0.287715	23.7019	.00000
Slope	6.62128E-3	3.44714E-4	19.208	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	46.42884	1	46.42884	368.9492	.00000
Error	5.788674	46	.125841		
Total (Corr.)	52.217509	47			

Correlation Coefficient = 0.942944   R-squared = 88.91 percent
Stnd. Error of Est. = 0.35474

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K210016   Independent variable: dnk210016

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	5.97159	0.564853	10.5719	.00000
Slope	6.98959E-3	6.77673E-4	10.3141	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	29.55107	1	29.55107	106.3806	.00000
Error	6.389084	23	.277786		
Total (Corr.)	35.940156	24			

Correlation Coefficient = 0.906769   R-squared = 82.22 percent
Stnd. Error of Est. = 0.527054

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: E11200   Independent variable: del1200

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	2.59871	0.563975	4.60785	.00366
Slope	5.53004E-3	1.01399E-3	5.45377	.00158

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	5.164701	1	5.164701	29.74360	.00158
Error	1.0418448	6	.1736408		
Total (Corr.)	6.2065462	7			

Correlation Coefficient = 0.912216   R-squared = 83.21 percent
Stnd. Error of Est. = 0.416702

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: E11204   Independent variable: del1204

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	3.05273	0.311445	9.80185	.00000
Slope	3.25517E-3	5.47392E-4	5.94669	.00007

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	4.442044	1	4.442044	35.36307	.00007
Error	1.507350	12	.125613		
Total (Corr.)	5.949394	13			

Correlation Coefficient = 0.864082   R-squared = 74.66 percent
Stnd. Error of Est. = 0.354419

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: E112010   Independent variable: del12010

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	1.68379	0.650413	2.58881	.01853
Slope	4.10871E-3	7.70403E-4	5.33319	.00005

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	4.081843	1	4.081843	28.44292	.00005
Error	2.583179	18	.143510		
Total (Corr.)	6.665022	19			

Correlation Coefficient = 0.782577   R-squared = 61.24 percent
Stnd. Error of Est. = 0.378827

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: E112016   Independent variable: del12016

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	2.25415	0.537061	4.1972	.00105
Slope	2.78735E-3	6.74188E-4	4.13438	.00118

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	.546208	1	.546208	17.09308	.00118
Error	.415414	13	.031955		
Total (Corr.)	.961623	14			

Correlation Coefficient = 0.753662   R-squared = 56.80 percent
Stnd. Error of Est. = 0.178759

Regression Analysis - Exponential model: Y = exp(a+bX)
```
------------------------------------------------------------------------
Dependent variable: P1200                    Independent variable: dnp1200
------------------------------------------------------------------------
                              Standard          T          Prob.
Parameter        Estimate       Error         Value        Level
------------------------------------------------------------------------
Intercept       -0.992936      0.248188      -4.00073      .00035
Slope           7.29628E-3     5.75441E-4    12.6795       .00000
------------------------------------------------------------------------

                      Analysis of Variance
------------------------------------------------------------------------
Source          Sum of Squares   Df  Mean Square  F-Ratio   Prob. Level
Model              54.81822       1    54.81822   160.7685      .00000
Error              10.911236     32     .340976
------------------------------------------------------------------------
Total (Corr.)      65.729461     33

Correlation Coefficient = 0.913235        R-squared =  83.40 percent
Stnd. Error of Est. = 0.583932
```

Regression Analysis - Exponential model: Y = exp(a+bX)
```
------------------------------------------------------------------------
Dependent variable: P1204                    Independent variable: dnp1204
------------------------------------------------------------------------
                              Standard          T          Prob.
Parameter        Estimate       Error         Value        Level
------------------------------------------------------------------------
Intercept       -1.15077       0.420045      -2.73964      .01520
Slope           6.2807E-3      8.1507E-4      7.70571      .00000
------------------------------------------------------------------------

                      Analysis of Variance
------------------------------------------------------------------------
Source          Sum of Squares   Df  Mean Square  F-Ratio   Prob. Level
Model              34.587181      1    34.587181  59.37795      .00000
Error               8.737379     15     .582492
------------------------------------------------------------------------
Total (Corr.)      43.324560     16

Correlation Coefficient = 0.893492        R-squared =  79.83 percent
Stnd. Error of Est. = 0.763212
```

Regression Analysis - Exponential model: Y = exp(a+bX)
```
------------------------------------------------------------------------
Dependent variable: P12010                   Independent variable: dnp12010
------------------------------------------------------------------------
                              Standard          T          Prob.
Parameter        Estimate       Error         Value        Level
------------------------------------------------------------------------
Intercept       -0.601202      0.241469      -2.48977      .02170
Slope           5.18172E-3     3.94092E-4    13.1485       .00000
------------------------------------------------------------------------

                      Analysis of Variance
------------------------------------------------------------------------
Source          Sum of Squares   Df  Mean Square  F-Ratio   Prob. Level
Model              43.88805       1    43.88805   172.8827      .00000
Error               5.077206     20     .253860
------------------------------------------------------------------------
Total (Corr.)      48.965261     21

Correlation Coefficient = 0.946737        R-squared =  89.63 percent
Stnd. Error of Est. = 0.503846
```

Regression Analysis - Exponential model: Y = exp(a+bX)
```
------------------------------------------------------------------------
Dependent variable: P12016                   Independent variable: dnp12016
------------------------------------------------------------------------
                              Standard          T          Prob.
Parameter        Estimate       Error         Value        Level
------------------------------------------------------------------------
Intercept       -2.81699       0.600547      -4.69071      .00008
Slope           7.34071E-3     9.70587E-4     7.56317      .00000
------------------------------------------------------------------------

                      Analysis of Variance
------------------------------------------------------------------------
Source          Sum of Squares   Df  Mean Square  F-Ratio   Prob. Level
Model              89.922497      1    89.922497  57.20147      .00000
Error              40.872809     26    1.572031
------------------------------------------------------------------------
Total (Corr.)     130.79531      27

Correlation Coefficient = 0.82916         R-squared =  68.75 percent
Stnd. Error of Est. = 1.25381
```

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K11200   Independent variable: dnk11200

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	6.72563	0.164998	40.7619	.00000
Slope	6.97454E-3	3.21185E-4	21.7151	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	35.76259	1	35.76259	471.5435	.00000
Error	4.929701	65	.075842		
Total (Corr.)	40.692293	66			

Correlation Coefficient = 0.937472   R-squared = 87.89 percent
Stnd. Error of Est. = 0.275393

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K11204   Independent variable: dnk11204

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	6.8686	0.163999	41.8819	.00000
Slope	5.59056E-3	2.91482E-4	19.1798	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	40.84505	1	40.84505	367.8647	.00000
Error	5.107508	46	.111033		
Total (Corr.)	45.952553	47			

Correlation Coefficient = 0.94279   R-squared = 88.89 percent
Stnd. Error of Est. = 0.333216

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K112010   Independent variable: dnk112010

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	4.95519	0.346262	14.3105	.00000
Slope	6.46935E-3	4.13009E-4	15.664	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	45.35210	1	45.35210	245.3596	.00000
Error	15.711341	85	.184839		
Total (Corr.)	61.063438	86			

Correlation Coefficient = 0.861803   R-squared = 74.27 percent
Stnd. Error of Est. = 0.429929

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: P12016   Independent variable: dnp12016

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	-0.866036	0.37644	-2.30059	.03520
Slope	4.60574E-3	5.95737E-4	7.73117	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	23.080752	1	23.080752	59.77104	.00000
Error	6.178445	16	.386153		
Total (Corr.)	29.259197	17			

Correlation Coefficient = 0.888165   R-squared = 78.88 percent
Stnd. Error of Est. = 0.621412

Regression Analysis - Exponential model: Y = exp(a+bX)
```
-----------------------------------------------------------------------
Dependent variable: E21200                    Independent variable: dne21200
-----------------------------------------------------------------------
                        Standard        T         Prob.
Parameter    Estimate    Error        Value       Level
-----------------------------------------------------------------------
Intercept    1.76593     0.105175     16.7903     .00000
Slope        7.36038E-3  1.93852E-4   37.969      .00000
-----------------------------------------------------------------------

                    Analysis of Variance
-----------------------------------------------------------------------
Source         Sum of Squares   Df  Mean Square   F-Ratio   Prob. Level
Model              87.8200       1    87.8200     1441.646    .00000
Error               5.908894    97    .060916
-----------------------------------------------------------------------
Total (Corr.)      93.728852    98

Correlation Coefficient = 0.967966      R-squared = 93.70 percent
Stnd. Error of Est. = 0.246813
```

Regression Analysis - Exponential model: Y = exp(a+bX)
```
-----------------------------------------------------------------------
Dependent variable: E21204                    Independent variable: dne21204
-----------------------------------------------------------------------
                        Standard        T         Prob.
Parameter    Estimate    Error        Value       Level
-----------------------------------------------------------------------
Intercept    2.76024     0.134204     20.5675     .00000
Slope        5.13917E-3  2.56191E-4   20.0599     .00000
-----------------------------------------------------------------------

                    Analysis of Variance
-----------------------------------------------------------------------
Source         Sum of Squares   Df  Mean Square   F-Ratio   Prob. Level
Model              24.26484      1    24.26484    402.4009    .00000
Error               2.351706    39    .060300
-----------------------------------------------------------------------
Total (Corr.)      26.616546    40

Correlation Coefficient = 0.954801      R-squared = 91.16 percent
Stnd. Error of Est. = 0.245561
```

Regression Analysis - Exponential model: Y = exp(a+bX)
```
-----------------------------------------------------------------------
Dependent variable: E212010                   Independent variable: dne212010
-----------------------------------------------------------------------
                        Standard        T         Prob.
Parameter    Estimate    Error        Value       Level
-----------------------------------------------------------------------
Intercept    3.19372     0.073577     43.4066     .00000
Slope        3.71192E-3  9.44866E-5   39.2852     .00000
-----------------------------------------------------------------------

                    Analysis of Variance
-----------------------------------------------------------------------
Source         Sum of Squares   Df  Mean Square   F-Ratio   Prob. Level
Model              12.2490       1    12.2490     1543.325    .00000
Error               .365092     46    .007937
-----------------------------------------------------------------------
Total (Corr.)      12.614125    47

Correlation Coefficient = 0.985422      R-squared = 97.11 percent
Stnd. Error of Est. = 0.0890886
```

Regression Analysis - Exponential model: Y = exp(a+bX)
```
-----------------------------------------------------------------------
Dependent variable: E212016                   Independent variable: dne212016
-----------------------------------------------------------------------
                        Standard        T         Prob.
Parameter    Estimate    Error        Value       Level
-----------------------------------------------------------------------
Intercept    2.60589     0.161503     16.1352     .00000
Slope        3.97485E-3  2.10659E-4   18.8687     .00000
-----------------------------------------------------------------------

                    Analysis of Variance
-----------------------------------------------------------------------
Source         Sum of Squares   Df  Mean Square   F-Ratio   Prob. Level
Model               4.33491      1     4.33491    356.0270    .00000
Error                .560087    46     .012176
-----------------------------------------------------------------------
Total (Corr.)        4.895000    47

Correlation Coefficient = 0.941053      R-squared = 88.56 percent
Stnd. Error of Est. = 0.110344
```

Regression Analysis - Exponential model: Y = exp(a+bX)

| Dependent variable: K21200 | | | Independent variable: dnk21200 | |

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	8.13388	0.298658	27.2348	.00000
Slope	6.96735E-3	4.81963E-4	14.4562	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	49.32130	1	49.32130	208.9811	.00000
Error	8.968319	38	.236008		
Total (Corr.)	58.289618	39			

Correlation Coefficient = 0.91986   R-squared = 84.61 percent
Stnd. Error of Est. = 0.485807

Regression Analysis - Exponential model: Y = exp(a+bX)

| Dependent variable: K21204 | | | Independent variable: dnk21204 | |

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	6.86583	0.290803	23.6099	.00000
Slope	6.27431E-3	4.39502E-4	14.276	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	93.92307	1	93.92307	203.8028	.00000
Error	15.208139	33	.460853		
Total (Corr.)	109.13121	34			

Correlation Coefficient = 0.927709   R-squared = 86.06 percent
Stnd. Error of Est. = 0.678861

Regression Analysis - Exponential model: Y = exp(a+bX)

| Dependent variable: K212010 | | | Independent variable: dnk212010 | |

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	6.26179	0.484432	12.926	.00000
Slope	6.56798E-3	6.00369E-4	10.9399	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	17.30103	1	17.30103	119.6816	.00000
Error	3.324852	23	.144559		
Total (Corr.)	20.625881	24			

Correlation Coefficient = 0.915861   R-squared = 83.88 percent
Stnd. Error of Est. = 0.380209

Regression Analysis - Exponential model: Y = exp(a+bX)

| Dependent variable: K212016 | | | Independent variable: dnk212016 | |

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	6.52881	0.524022	12.459	.00000
Slope	5.75833E-3	5.90513E-4	9.75139	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	24.394804	1	24.394804	95.08965	.00000
Error	5.900542	23	.256545		
Total (Corr.)	30.295347	24			

Correlation Coefficient = 0.897348   R-squared = 80.52 percent
Stnd. Error of Est. = 0.506503

Regression Analysis - Exponential model: Y = exp(a+bX)
```
---------------------------------------------------------------------------
Dependent variable: E11500                    Independent variable: del1500
---------------------------------------------------------------------------
                            Standard         T          Prob.
Parameter      Estimate     Error          Value        Level
---------------------------------------------------------------------------
Intercept      2.33204      0.360524       6.46848      .00003
Slope          5.54424E-3   7.08821E-4     7.82177      .00000
---------------------------------------------------------------------------
```

Analysis of Variance
```
---------------------------------------------------------------------------
Source          Sum of Squares   Df   Mean Square   F-Ratio    Prob. Level
Model               4.939833      1    4.939833      61.18015      .00000
Error                .968909     12     .080742
---------------------------------------------------------------------------
Total (Corr.)       5.908742     13
```

Correlation Coefficient = 0.914342   R-squared = 83.60 percent
Stnd. Error of Est. = 0.284152

Regression Analysis - Exponential model: Y = exp(a+bX)
```
---------------------------------------------------------------------------
Dependent variable: E11504                    Independent variable: del504
---------------------------------------------------------------------------
                            Standard         T          Prob.
Parameter      Estimate     Error          Value        Level
---------------------------------------------------------------------------
Intercept      2.63164      0.375165       7.01463      .00000
Slope          3.21019E-3   4.63401E-4     6.92746      .00000
---------------------------------------------------------------------------
```

Analysis of Variance
```
---------------------------------------------------------------------------
Source          Sum of Squares   Df   Mean Square   F-Ratio    Prob. Level
Model               3.030541      1    3.030541      47.98965      .00000
Error               1.010398     16     .063150
---------------------------------------------------------------------------
Total (Corr.)       4.040939     17
```

Correlation Coefficient = 0.866002   R-squared = 75.00 percent
Stnd. Error of Est. = 0.251296

Regression Analysis - Exponential model: Y = exp(a+bX)
```
---------------------------------------------------------------------------
Dependent variable: e115010                   Independent variable: de115010
---------------------------------------------------------------------------
                            Standard         T          Prob.
Parameter      Estimate     Error          Value        Level
---------------------------------------------------------------------------
Intercept      -2.0938      0.992395       -2.10984     .05000
Slope          8.05393E-3   1.25686E-3     6.40797      .00001
---------------------------------------------------------------------------
```

Analysis of Variance
```
---------------------------------------------------------------------------
Source          Sum of Squares   Df   Mean Square   F-Ratio    Prob. Level
Model               4.531550      1    4.531550      41.06204      .00001
Error               1.876096     17     .110359
---------------------------------------------------------------------------
Total (Corr.)       6.407646     18
```

Correlation Coefficient = 0.840958   R-squared = 70.72 percent
Stnd. Error of Est. = 0.332203

Regression Analysis - Exponential model: Y = exp(a+bX)
```
---------------------------------------------------------------------------
Dependent variable: E115016                   Independent variable: de115016
---------------------------------------------------------------------------
                            Standard         T          Prob.
Parameter      Estimate     Error          Value        Level
---------------------------------------------------------------------------
Intercept      -0.219869    0.295128       -0.744995    .46351
Slope          5.43054E-3   3.40137E-4     15.9657      .00000
---------------------------------------------------------------------------
```

Analysis of Variance
```
---------------------------------------------------------------------------
Source          Sum of Squares   Df   Mean Square   F-Ratio    Prob. Level
Model               6.07832       1    6.07832       254.9041      .00000
Error                .572292     24     .023846
---------------------------------------------------------------------------
Total (Corr.)       6.650613     25
```

Correlation Coefficient = 0.956007   R-squared = 91.39 percent
Stnd. Error of Est. = 0.15442

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: P1500   Independent variable: dnp1500

                              Standard   T   Prob.
Parameter   Estimate   Error   Value   Level

Intercept   -1.26273   0.270732   -4.66414   .00003
Slope   7.39144E-3   5.49877E-4   13.442   .00000

                        Analysis of Variance

Source   Sum of Squares   Df   Mean Square   F-Ratio   Prob. Level
Model   51.84782   1   51.84782   180.6870   .00000
Error   12.051825   42   .286948

Total (Corr.)   63.899645   43

Correlation Coefficient = 0.900774   R-squared = 81.14 percent
Stnd. Error of Est. = 0.535675

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: P1504   Independent variable: dnp1504

                              Standard   T   Prob.
Parameter   Estimate   Error   Value   Level

Intercept   -0.391305   0.254276   -1.5389   .14122
Slope   4.43776E-3   4.97679E-4   8.91691   .00000

                        Analysis of Variance

Source   Sum of Squares   Df   Mean Square   F-Ratio   Prob. Level
Model   25.242518   1   25.242518   79.51131   .00000
Error   5.714474   18   .317471

Total (Corr.)   30.956992   19

Correlation Coefficient = 0.902998   R-squared = 81.54 percent
Stnd. Error of Est. = 0.563445

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: P15010   Independent variable: dnp15010

                              Standard   T   Prob.
Parameter   Estimate   Error   Value   Level

Intercept   -6.58683   0.329051   -20.0177   .00000
Slope   0.0118416   5.39503E-4   21.9491   .00000

                        Analysis of Variance

Source   Sum of Squares   Df   Mean Square   F-Ratio   Prob. Level
Model   182.84000   1   182.84000   481.7651   .00000
Error   7.210901   19   .379521

Total (Corr.)   190.05090   20

Correlation Coefficient = 0.980846   R-squared = 96.21 percent
Stnd. Error of Est. = 0.616053

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: P15016   Independent variable: dnp15016

                              Standard   T   Prob.
Parameter   Estimate   Error   Value   Level

Intercept   -2.94695   0.762001   -3.86738   .00096
Slope   7.08643E-3   1.13046E-3   6.2686   .00000

                        Analysis of Variance

Source   Sum of Squares   Df   Mean Square   F-Ratio   Prob. Level
Model   87.495885   1   87.495885   39.29531   .00000
Error   44.532479   20   2.226624

Total (Corr.)   132.02836   21

Correlation Coefficient = 0.814067   R-squared = 66.27 percent
Stnd. Error of Est. = 1.49219

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K11500   Independent variable: dnk11500

                              Standard   T   Prob.
Parameter   Estimate   Error   Value   Level

Intercept   6.58855   0.166467   39.5787   .00000
Slope   6.41284E-3   3.1339E-4   20.4628   .00000

                    Analysis of Variance

Source   Sum of Squares   Df Mean Square   F-Ratio   Prob. Level
Model   48.72665   1   48.72665   418.7280   .00000
Error   11.520458   99   .116368

Total (Corr.)   60.247110 100

Correlation Coefficient = 0.899322   R-squared = 80.88 percent
Stnd. Error of Est. = 0.341128

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K11504   Independent variable: dnk11504

                              Standard   . T   Prob.
Parameter   Estimate   Error   Value   Level

Intercept   5.44764   0.200747   27.1368   .00000
Slope   6.51524E-3   2.61459E-4   24.9188   .00000

                    Analysis of Variance

Source   Sum of Squares   Df Mean Square   F-Ratio   Prob. Level
Model   59.22254   1   59.22254   620.9456   .00000
Error   7.153107   75   .095375

Total (Corr.)   66.375649   76

Correlation Coefficient = 0.944581   R-squared = 89.22 percent
Stnd. Error of Est. = 0.308828

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K115010   Independent variable: dnk115010

                              Standard   T   Prob.
Parameter   Estimate   Error   Value   Level

Intercept   2.09287   0.627903   3.3331   .00180
Slope   9.55994E-3   8.20806E-4   11.647   .00000

                    Analysis of Variance

Source   Sum of Squares   Df Mean Square   F-Ratio   Prob. Level
Model   10.03067   1   10.03067   135.6530   .00000
Error   3.105631   42   .073944

Total (Corr.)   13.136300   43

Correlation Coefficient = 0.873833   R-squared = 76.36 percent
Stnd. Error of Est. = 0.271926

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K115016   Independent variable: dnk115016

                              Standard   T   Prob.
Parameter   Estimate   Error   Value   Level

Intercept   3.31537   0.383584   8.64312   .00000
Slope   7.73948E-3   4.49237E-4   17.2281   .00000

                    Analysis of Variance

Source   Sum of Squares   Df Mean Square   F-Ratio   Prob. Level
Model   24.30991   1   24.30991   296.8069   .00000
Error   4.422859   54   .081905

Total (Corr.)   28.732766   55

Correlation Coefficient = 0.91982   R-squared = 84.61 percent
Stnd. Error of Est. = 0.28619

Regression Analysis - Exponential model: Y = exp(a+bX)
```
------------------------------------------------------------------------------
Dependent variable: E21500                          Independent variable: dne21500
------------------------------------------------------------------------------
                              Standard            T              Prob.
Parameter        Estimate     Error             Value           Level
------------------------------------------------------------------------------
Intercept        1.29433      0.1097            11.7988          .00000
Slope            7.89805E-3   2.13653E-4        36.9668          .00000
------------------------------------------------------------------------------

                         Analysis of Variance
------------------------------------------------------------------------------
Source           Sum of Squares   Df  Mean Square   F-Ratio   Prob. Level
Model            87.5769           1   87.5769       1366.542    .00000
Error            7.88264         123   .06409
------------------------------------------------------------------------------
Total (Corr.)    95.45952        124

Correlation Coefficient = 0.957823        R-squared =  91.74 percent
Stnd. Error of Est. = 0.253153
```

Regression Analysis - Exponential model: Y = exp(a+bX)
```
------------------------------------------------------------------------------
Dependent variable: E21504                          Independent variable: dne21504
------------------------------------------------------------------------------
                              Standard            T              Prob.
Parameter        Estimate     Error             Value           Level
------------------------------------------------------------------------------
Intercept        1.96528      0.156253          12.5775          .00000
Slope            5.23009E-3   2.18193E-4        23.97            .00000
------------------------------------------------------------------------------

                         Analysis of Variance
------------------------------------------------------------------------------
Source           Sum of Squares   Df  Mean Square   F-Ratio   Prob. Level
Model            23.33567          1   23.33567      574.5608    .00000
Error            2.396272         59   .040615
------------------------------------------------------------------------------
Total (Corr.)    25.731937        60

Correlation Coefficient = 0.9523          R-squared =  90.69 percent
Stnd. Error of Est. = 0.201531
```

Regression Analysis - Exponential model: Y = exp(a+bX)
```
------------------------------------------------------------------------------
Dependent variable: E215010                         Independent variable: dne15010
------------------------------------------------------------------------------
                              Standard            T              Prob.
Parameter        Estimate     Error             Value           Level
------------------------------------------------------------------------------
Intercept        -0.889025    0.529778          -1.67811         .10042
Slope            0.0117268    6.83454E-4        17.1581          .00000
------------------------------------------------------------------------------

                         Analysis of Variance
------------------------------------------------------------------------------
Source           Sum of Squares   Df  Mean Square   F-Ratio   Prob. Level
Model            32.28466          1   32.28466      294.4010    .00000
Error            4.825137         44   .109662
------------------------------------------------------------------------------
Total (Corr.)    37.109793        45

Correlation Coefficient = 0.932725        R-squared =  87.00 percent
Stnd. Error of Est. = 0.331153
```

Regression Analysis - Exponential model: Y = exp(a+bX)
```
------------------------------------------------------------------------------
Dependent variable: E215016                         Independent variable: dne215016
------------------------------------------------------------------------------
                              Standard            T              Prob.
Parameter        Estimate     Error             Value           Level
------------------------------------------------------------------------------
Intercept        0.450063     0.135986          3.30962          .00157
Slope            6.44301E-3   1.61418E-4        39.9152          .00000
------------------------------------------------------------------------------

                         Analysis of Variance
------------------------------------------------------------------------------
Source           Sum of Squares   Df  Mean Square   F-Ratio   Prob. Level
Model            22.0397           1   22.0397       1593.221    .00000
Error            .843840          61   .013833
------------------------------------------------------------------------------
Total (Corr.)    22.883557        62

Correlation Coefficient = 0.981389        R-squared =  96.31 percent
Stnd. Error of Est. = 0.117616
```

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K21500   Independent variable: dnk21500

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	4.82398	0.221183	21.8099	.00000
Slope	0.0116318	4.33441E-4	26.836	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	51.13161	1	51.13161	720.1691	.00000
Error	2.200983	31	.070999		

| Total (Corr.) | 53.332591 | 32 | | | |

Correlation Coefficient = 0.979148   R-squared = 95.87 percent
Stnd. Error of Est. = 0.266457

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K21504   Independent variable: dnk21504

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	6.61729	0.464207	14.255	.00000
Slope	6.92548E-3	5.75409E-4	12.0357	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	50.44192	1	50.44192	144.8592	.00000
Error	11.839255	34	.348213		

| Total (Corr.) | 62.281175 | 35 | | | |

Correlation Coefficient = 0.899948   R-squared = 80.99 percent
Stnd. Error of Est. = 0.590096

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K215010   Independent variable: dnk215010

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	5.7481	0.414446	13.8694	.00000
Slope	5.89133E-3	4.68958E-4	12.5626	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	91.46906	1	91.46906	157.8190	.00000
Error	27.819945	48	.579582		

| Total (Corr.) | 119.28900 | 49 | | | |

Correlation Coefficient = 0.875663   R-squared = 76.68 percent
Stnd. Error of Est. = 0.761303

Regression Analysis - Exponential model: Y = exp(a+bX)

Dependent variable: K215016   Independent variable: dnk215016

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	7.9956	0.563614	14.1863	.00000
Slope	3.9836E-3	5.72342E-4	6.96018	.00000

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	14.640082	1	14.640082	48.44406	.00000
Error	4.835295	16	.302206		

| Total (Corr.) | 19.475377 | 17 | | | |

Correlation Coefficient = 0.867019   R-squared = 75.17 percent
Stnd. Error of Est. = 0.549733