
By

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DEDICATION

This work is dedicated to my fond family; Awatif, Mohamed, Huda, Sara and Ahmed for their great love, care and affection.
DECLARATION

I hereby declare that this thesis, submitted in candidature for the degree of Doctor of Philosophy of the University of Khartoum, has not been submitted concurrently for any other degree. It is a result of my own investigation and any assistance is acknowledged.

Candidate ........................................

Supervisor  ........................................
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patience, assistance and encouragement.
ABSTRACT

Effects of Mixing Some Wood and Non-wood lignocellulosic Materials on the Properties of Cement and Resin Bonded Particleboard

A rapid development of the wood–based panel industry has been reported in recent literature. Major growth opportunities are expected to continue in particleboard market. The supply for wood which is so far the main raw material for particleboard has become problematic. Particleboard industry is intensifying efforts to find suitable substitutes for wood. In recent years effective utilization of thinning produce, wood and agricultural residues has gained increasing importance. Several attempts were made to mix different types of raw materials for making particleboard. Particleboard production is directly linked to some of the key issues of our times, namely; resources conservation, housing and the environment.

This study investigated the effect of some conventional treatments on compatibility of cement and some wood and non-wood lignocellulosic materials. It also examined the effect of blending different proportions of the lignocellulosic materials on the properties of particleboards made using cement (inorganic binder) and Urea formaldehyde (organic binder). The three lignocellulosic materials used were *Acacia nilotica* sawdust, bagasse and cotton stalks. They are waste materials of widely cultivated species in Sudan. They were collected from EL Suki sawmill, EL Gunied sugar factory and the Fields of EL Kamlin state.

Four experiments were carried out. The first was conducted to investigate the effect of six treatments {control (untreated material), control +3%CaCl₂, hot water extraction, Hot water extraction +3%CaCl₂,1%NaOH extraction, and 1%NaOH extraction +3%CaCl₂} on
the hydration characteristics of the three lignocellulosic materials with cement. Two Dewar flasks and a digital thermocouple were used. The maximum hydration temperature, time to reach maximum temperature and rise in temperature above the ambient were determined for each lignocellulosic material. The most suitable treatment common to all materials was the 1%NaOH+3%CaCl₂ . The average maximum hydration temperatures were 63.87 °C, for bagasse, 67.87 °C for cotton stalks and 67.9 °C for sunt sawdust. Bagasse was the least responsive material to the treatments used, followed by cotton stalks and then sunt sawdust.

In the second experiment, extractive contents, lignin content, hot water and weak alkali solubility of the three lignocellulosic materials were determined. The results of the above mentioned tests revealed that bagasse attained the highest results of hot water and 1% NaOH extraction. The results were therefore consistent with the hydration characteristics observed.

In the third experiment different mixtures and ratios were used to manufacture laboratory size cement bonded particle boards. Analysis of variance and Duncan Multiple Range Test were used to study the significance of the variations, if any. Reasonable panel properties were obtained from the three lignocellulosic materials either pure or mixed using different cement/wood ratios (3:1, 3.5:1 and 4:1).

In the fourth experiment ten different mixtures of the three lignocellulosic materials (Nine homogenous, One layered) of urea formaldehyde resin bonded particleboards were manufactured under the laboratory conditions. The minimum property requirements of commercial particleboard standards EN 312:2003 for MOR, MOE were met or exceeded at 10% resin content level except for pure cotton stalks boards. Addition of bagasse particles to sunt sawdust or cotton stalks or to their
mixtures improved the properties of boards made of their respective blends.
الملخص العربي

أثر خلط بعض المواد اللجنو سليولوزية الخشبية و غير الخشبية
على خصائص الخشب الحبيبي: الملصق بإسمنت وبلاستيك

لقد رصدت الدراسات الحديثة تطوراً سريعاً ومضطراً في مجال صناعة الألواح الخشبية المركبة. ويتوقع استمرار المزيد من فرص هذا النمو في مجال اسواق الخشب الحبيبي. ان إمدادات الاخشاب التي تشكل حاليا المصدر الرئيسي للمادة الخام لصناعة الخشب الحبيبي، أصبحت من العقبات والمشكلات التي تواجه هذه الصناعة. ولذلك فان القائمين على أمر صناعة الخشب الحبيبي يضافون من جهودهم لإيجاد البديل المناسبة للخشب، وفي السنوات الأخيرة وجد الاستغلال الفعال للاخشاب الناتجة من تخفيف أشجار الغابات (الشلخ) ومخلفات الاخشاب والمخلفات الزراعية الأخرى، اهتم ما متزايداً. وهذا كما وحولت عدة لخليط أنواع مختلفة من المادة الخام لصناعة الخشب الحبيبي، والخشب الحبيبي من المنتجات التي ترتبط مباشرة ببعض الحاجيات الأساسية لزماننا، وتحديداً، المحافظة على المواد والإسكان والبيئة.

بحثت هذه الدراسة أثر بعض المفاهيم التقليدية على توافقات الأمسنت وبعض المواد اللجنو سليولوزية الخشبية و غير الخشبية. كما تم اختيار أثر خلط نسب مختلفة من المواد على خصائص الخشب الحبيبي المصنع باستعمال الأمسنت (مادة لاصقة غير عضوية) والهولوكوريورا. فورما لديها بد (مادة لاصقة عضوية). استعملت في هذه الدراسة ثلاث مواد لجنو سليولوزية هي: نشأة خشب اشجار السنت (Acacia nilotica)، الباقس، وسيقان القطن وهي جميعها مخلفات انواع مخالفة تكثر زراعتها في السودان. جمعت هذه المخلفات من مصنع السوكي لنشر الاخشاب، مصنوع سكر الجنيد، وحقول القطن في محافظة الكا إيلين بولاية الجزيرة.

لقد تم إجراء أربع تجارب في هذه الدراسة، التجربة الأولى أجريت لدراسة تأثير ست معاملات للمادة الخام لمعرفة أنها على خواص تشرب الأمسنت (Hydration characteristics) للمواد اللجنو سليولوزية الثلاث مع الأمسنت. و المعاملات هي: (الашهرة (المواد بدون معاملة) الاستخلاص بما لماء الساخن، الاستخلاص بحلول هايبركسيم الصوديوم بنسبة تركيز 1% وثلاث معا ملات أخرى تتمثل في إضافة كلوريد الكالسيوم (3% من وزن الأمسنت) لكل من المعا ملات الثلاث السابقة. استخدمت في هذه التجربة دورقا ن خصصان (Dewar flasks)
Thermocouple digital (Digital thermocouple).

Time to reach maximum hydration temperature ($t_2$) (Maximum hydration temperature ($T_2$))

Rise in temperature above the ambient (ambient)

In the second experiment, the temperature of the water and the temperature of the burner were measured separately and the temperature difference was also calculated. The water used was tap water, and the burner was a gas burner. The water was placed in a beaker and the burner was placed on top. The beaker was placed on a scale and the temperature difference was measured.

In the third experiment, the water was boiled in a beaker and the burner was placed on top. The beaker was placed on a scale and the temperature difference was measured.

In the fourth experiment, the water was boiled in a beaker and the burner was placed on top. The beaker was placed on a scale and the temperature difference was measured.

The temperature difference was then calculated and compared to the results obtained in the previous experiments. The results showed that the temperature difference was consistent across all experiments.

In the fifth experiment, the water was boiled in a beaker and the burner was placed on top. The beaker was placed on a scale and the temperature difference was measured.

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Chapter One

Introduction and objectives

1.1. Introduction

Wood is the most commonly used natural raw material. It serves as a raw material for wood composites such as plywood, particleboard and fiberboard. Individual cell wall layers of wood are helically filament-wound composites with cellulose microfibrils as the filaments embedded in a matrix of lignin and hemicelluloses.

Wood is still a widely used structural material in the world because it is comfortable for human life. However, because it is a natural material, it has several drawbacks, such as liability to checks, formation of knots, limited widths and variability in performance along and across the grain.

In order to avoid such defects and to enhance the quality, wood composites or wood-based materials are developed.

A strong growth of the wood-based industry has been reported in the recent literature. Cullity (1988) mentioned that panel production has doubled during the period 1965-1985 from 42 million cubic meters to 109 million m$^3$. Much of this growth occurred in the decade 1965-1975.

Particleboard in particular exploded from 9 million m$^3$ in 1965 to 44.5 million m$^3$ in 1985 and "showing every indication of holding onto the lead". The total production of wood-based panels was 24 million cubic meters in 1989 within the European Economic Community (EEC), of which 83 % was particleboard. The total consumption of wood-based panels was 30 million cubic meters of which 70 % was resin bonded particleboard (Dinwoodi 1996).

Pease (1989) reported that major growth opportunities are forecasted in the panel market. This growth is expected to continue and "there is no fundamental reason why it should end". The annual survey of the wood
based panels by World Wood Journal (Anonymous 1988) shows a renewed strength in particleboard and more interest in mineral boards and panels made from bagasse.

F.A.O. (2002) reported that the production of particleboard in Europe for the year 2001 was 37.213 million cubic meters and for North America was 31.563 million m³. It was forecasted that an overall continued growth will prevail in the coming years. The total production of particleboard is expected to be 41.63 million m³ in Europe and 33.08 million m³ in North America (Anonymous. 2004). The consumption of wood-based panels was projected to be 2375 thousands cubic meters in Africa in the year 2010 and 6000 cubic meters in the Sudan. The consumption of particleboard in Africa was projected to be about 562 thousands cubic meters (Anonymous. 2003).

Subiyanto, and Kawai (1996) reported that considerable change in the housing and building construction industries have been taking place, particularly with regards to composite panel products bonded with organic or inorganic binders are without exception.

Wood particles bonded with ordinary Portland cement are becoming more prevalent in a number of countries around the world. Expanding its material base, discovering new methods of manufacturing technologies and modifying the inorganic binders are some of the aspects that are gaining momentum.

The supply of wood which so far has been the common raw material for particleboard manufacture has become problematic (Vermass 1981).

Fuller (1987) mentioned that the raw material prices are climbing due to decline in wood supply. There is clear evidence that the timber demand/supply will tighten significantly and will result in a switch to different types of wood or non-wood products.
Despite the extensive forest areas in many parts of the world, and the improved management of forests, the merchantable yield is still finite. Against the constantly increasing population and the resulting escalating demand for wood-based products, the supply may run short of meeting the demand.

Vermass (1981) mentioned that apart from the rapid development of the industry, there are many regions in the world where there is an acute shortage of wood or where wood is and has been very scarce.

In particleboard industry efforts are being intensified to find other suitable substitutes for wood. Apart from the utilization of biomass (hogged–up total bush and thinning produce including leaves) and bark, large quantities of agricultural residues and annual plants have been tried. The main long–term trends according to Fuller (1985) have been for the non-wood lignocellulosic materials to substitute for wood. This substitution has been encouraged by either the cost of wood or the technological inability of wood to perform in certain end-uses. In recent years, following the reduction in timber resources and degradation of global environment, effective utilization of thinning, fast growing resources and agricultural residues such as bagasse, has gained increasing importance.

Kozlowski et al. (1994) stated that the shortage of wood together with a need for waste utilization and availability of an annual abundance of plant residues inspired the production of boards from plant residues. These residues are especially appreciated in places where wood resources are few or limited. Flax, jute, cotton stalks and bagasse were used for particleboard production. Wood sawdust is sometimes added to these residues. One of the advantages of the boards produced from plant residues is the possibility of producing a wide spectrum of densities ranging from 300 to 750 Kg / m³.
For the production of particleboard from annual plant residues, urea-formaldehyde or urea-melamine formaldehyde synthetic resins are mainly used. In recent years, technologies have been developed to use gypsum and cement as binding materials.

Cement–bonded particleboards seem attractive in extending the use of wood waste and agricultural residues. These are otherwise environmental problems. In addition, the problem of formaldehyde emission is eliminated during production and usage of these inorganic bonded boards. Several problems have hindered the development of cement bonded particleboard. These difficulties include species sensitivity and heavy weight.

Being related to the housing and building industry, the acceptance of adopting new materials, traditionally is relatively slow, when compared to that of organic-bonded wood composites. In addition to that, an inherent manufacturing disadvantage of wood cement panels is the long curing period needed for cement to fully hydrate before attaining adequate strength. However, a number of research activities have been conducted on how to solve the problems of species sensitivity and cement hydration. Studies on shortening the pressing time are also being conducted. Subiyanto and Kawai (1996) concluded that thermosetting cement bonded particleboard prepared from albizia (*Paraseriethes falcataria* (L) Nicolson) and mixtures of hinoki (*Chamaecyparis obtuse* Entl.) and sugi (*Cryptomeria japonica* D. Don) wood particles can be produced with very short pressing time.

Cement bonded boards have proved to be durable and to have low production cost as well (Fernandez and Taja-on 2000). The incorporation of wood elements in these boards, greatly improves the mechanical properties of the matrix material while retaining its excellent fire resistance.
Several attempts were made in the past to mix different types of raw materials for making particleboard. Mohamed (1989) reported that particleboard can be manufactured from non-wood lignocellulosic materials with excellent properties. Conventional wood adhesives can be used successfully as binders for most of the non-wood lignocellulosic materials. The recent developments in adhesive industry have widened the range of the raw materials available for particleboard production. The properties of particleboard from non-wood lignocellulosic materials are comparable to those of wood particleboards and sometimes even better.

As it was stated by Marra (1970) particleboard is still a product that is directly linked to some of the key issues of our times; namely, resource conservation, pollution and housing. With regard to resources conservation, particleboard stands ready to double the product output of forests without increasing the cutting ratio. It has the highest conversion ratio of any wood process. It operates on residues and this is conservation at its highest level.

When considering the pollution, the impact of particleboard is direct. The types of raw materials used were formally burned or dumped in rivers as means of disposal. It is obvious that particleboard has a direct impact on housing both for construction and furnishing. The point is too well known to need further elaboration. Consequently, it is important that as much effort as possible is made towards the rational utilization of all fibrous materials for particleboard production.

The product is not as demanding in terms of raw materials and skilled labor as in plywood. It is a cheap product and its properties can be engineered. The principal drawbacks of solid wood such as variability in performance, anisotropy and limited widths, could be eliminated.
Apparently this will encourage the efficient utilization of all suitable fibrous materials particularly the under utilized wood species. The local population will then realize that the forests as such have a direct commercial value. This will enhance community involvement in forest management and forest protection and therefore induces an element of sustainability.

*Acacia nilotica* (L) Wild (sunt), is a hard and heavy timber, weighing about 58 pounds per cubic foot at 12 percent moisture content or a density of (0.83 g/cm³) as estimated by some researchers (Anonymous 1968 Nasroun 1979). Wood density has a significant influence not only on particleboard properties but also on processing. Particleboard made from lower density species has a greater bending strength, internal bond and modulus of elasticity. The reason for this lies in the fact that a given weight of particles from a light weight lignocellulosic material, occupies a greater volume than the same weight of similar particles from a dense wood. When these volumes of lignocellulosic materials are compressed to the dimensions of a board, a higher relative contact occurs for the low density wood due to a greater mean compression ratio (the ratio of the density of compressed wood to the natural non compressed wood density). Also boards made from dense wood become so heavy that they are difficult to handle (Moslemi 1974).

Several attempts were made in the past to mix different types of raw materials for particleboard manufacture. This was done to make use of lignocellulosic residues and or to improve or modify the quality of particleboard.

The three lignocellulosic materials used in this investigation were chosen because they are available in considerable amounts as residues of widely cultivated crops in Sudan. *Acacia nilotica* is grown for industrial processing for the production of railway sleepers. Cotton was grown for
ages as a cash crop and sugar cane is widely planted for sugar industry. Their residues need to be put in a better utilization rather than being burnt or dumped.

Previous studies have indicated that some lignocellulosic materials are not suitable for the manufacture of cement bonded particleboard. This characteristic varies with the type of material. The variation arises due to adverse effects on cement setting due to the presence of certain extractives (Kumar 1981, Sandermann et al. 1960, Sandermann and Schmitz 1966). The ability of wood to combine with Portland cement is termed compatibility. Hydration characteristics have been commonly used to assess the compatibility with cement of potential lignocellulosic materials.

The compatibility of wood with cement can be enhanced with several treatments. Hot water and weak alkali are among the common treatments used to extract the inhibitory substances in wood. Calcium chloride is one of the widely used accelerators of cement setting. These treatment methods were chosen to be used in this study. They are relatively cheap and easy to use. Sodium hydroxide (1 % solution) is found to be the most effective treatment for the three lignocellulosic materials under investigation.
1.2. Objectives

The objectives of this study were to:
1- Study the effect of conventional treatments on the compatibility of three wood and non-wood lignocellulosic materials widely cultivated in the Sudan with cement.
2- Examine the effect of blending wood and non-wood lignocellulosic materials using different cement to wood ratios for cement bonded particleboard.
3- Evaluate the effect of mixing different lignocellulosic materials on the properties of Urea formaldehyde bonded particleboard.
4- Compare properties of the various board types to the minimum property requirements specified in the commercial standards for manufactured particleboards.
2.1. Wood-Based Panel Materials

Wood-based panel materials are classified under the generic term wood composite boards, which are sheet materials containing a significant amount of wood in different forms; strips, veneers, chips, flakes or fibers. The categories of the wood-based panel products or wood composites are plywood, particleboard (including wood chip board and wood cement particleboard) and fiber building boards (TRADA 1985).

In general, particleboard is used as a generic term for all particle panel products which includes, flake board, wafer board, oriented strand board (OSB), and mineral bonded board. Particle panel products are defined as any wood-based panel product made of pieces of wood smaller than veneer sheets but longer than wood fiber (Ishihara 1996).

Particleboard is defined by Maloney (1977) as “A generic term for a panel manufactured from lignocellulosic materials (usually wood), primarily in the form of discrete pieces or particles, as distinguished from fibers, combined with a synthetic resin or other suitable binder and bonded together under heat and pressure in a hot press by a process in which the entire interparticle bond is created by the added binder, and to which other materials may have been added during manufacture to improve certain properties. Particleboards are further defined by the method of pressing. When the pressure is applied in the direction perpendicular to the faces, as in conventional multiplaten hot press, they are defined as flat-platen pressed; and when the applied pressure is parallel to the faces, they are defined as extruded".
Particleboard types can be classified by particle size and geometry, particle size differentiation between face and core, board density, type of resin, and method of manufacture (Haygreen and Bowyer 1982). Particleboards can be used in the buildings activities, furniture manufacture and kitchen fitments, constructional uses and Radio and Television boxes.

2.2. Raw Materials for Particleboards

2.2.1. Lignocellulosic materials

The use of natural fibers of vegetable origin to produce a composite material was old. It dates back to the use of straw and reeds to reinforce brickwork (Ashraf 1991). A wide range of wood and non-wood lignocellulosic materials can be used for particleboard production. The wood sources which can be utilized for particleboard manufacture can be in the form of round wood, slabs, edgings and off-cuts or from residues of furniture industries or other particulate wood from sawmills and other processes. The shortages of wood together with a need for the utilization of waste wood and availability of an annual abundance of plant residues inspired the production of boards from some non-wood lignocellulosic materials such as flax, jute, bagasse and cotton stalks (Kozlowski et al. 1994).

The fluctuating situation in annual plants production resulted in periodical lack of raw materials for plants operating on plant residues such as flax. The situation forced researchers to look for other raw materials including wood residues, such as sawdust and waste woodchips to fill in the gap. The use of these two wood residues improved some of the boards properties, especially those used in the furniture industry. In the beginning of 1990s, considerable market stimulation was noticed in the bast fiber industries in many parts of the world. This can be explained by the trend towards the preference of natural products. Another reason
was the discovery that fibrous plants cultivated on polluted areas can naturally decontaminate the soil from the heavy metals. Such plants can be used for lignocellulosic boards with no negative effect on the environment (Kozlowski et al. 1992).

2.2.1.1 Bagasse

Bagasse is a cellulose containing residue. It is a by-product of the sugar industry after the extraction of sugar from the cane (Vermass 1981). Sugar cane (*Saccharum spp.*) is a large, perennial tropical grass which belongs to the family *Gramineae*. Sugar cane industry is important in many tropical and sub tropical countries including Sudan (Cobley 1976). In many places of the world there is a surplus of bagasse and much of it is either burnt or dumped into rivers or seas (Kollmann et al. 1975). The chemical composition of bagasse is similar to that of wood as can be seen in Table 2.1.

Table 2.1 Chemical composition of bagasse and wood

<table>
<thead>
<tr>
<th></th>
<th>Bagasse</th>
<th>Beech</th>
<th>Pine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose %</td>
<td>46</td>
<td>45</td>
<td>42</td>
</tr>
<tr>
<td>Lignin %</td>
<td>23</td>
<td>23</td>
<td>29</td>
</tr>
<tr>
<td>Pentosans and</td>
<td>26</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>hexosans %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other components</td>
<td>5</td>
<td>10</td>
<td>7</td>
</tr>
</tbody>
</table>

(Source Hesch 1973).
Hesch (1973) mentioned that bagasse is the most important raw material among the non wood fibers at present. It is available in vast quantities which can be exploited economically for the production of particleboard. Dry bagasse consists of about 30 % pith, 58 % fiber and 12 % solubles (unextracted sugar) plus dirt, with the actual values vary somewhat according to origin (Grant et al. 1978). Rao (1984) stated that, in Cuba, where there is a shortage of forest resources and a need for making use of by-products of the sugar industry in a more profitable way, plants for manufacture of particleboard from bagasse were started quite early.

### 2.2.1.2. Cotton stalks

Cotton (*Gossypium spp.*) is one of the oldest cultivated plants. It belongs to the family *Malvaceae* (category of mallow plants). The species of cotton has many varieties. It grows up to two meters in height with a vertical branched stem, herbaceous to shrub-like shape (Vermass 1981). After the harvesting of the crop, entomologists insist on elimination of the old plants in order to create a closed season against various pests of cotton (Prentice 1972). Cotton residues must be uprooted and burned. The stalks are collected into heaps and then set alight (Munro 1987).

The cross section of the cotton stalk consists of the bark, followed by the bast and woody fibers and then the pith. The proportion of woody fibers decreases towards the top of the plant whereas the amount of bast fibers increases (Vermass 1981). The chemical composition of cotton stalks is shown by Mobarak (1983), as in Table 2.2.

Vermass (1981) mentioned that cotton stalk contains an amount of wood which can be considered as an excellent basic material for particleboard production. The disposal of cotton stalks became more and more a problem because of the recent concern about the environmental pollution. The residues can be utilized either for the production of particleboard or cement bonded boards.
2.2.1.3. *Acacia nilotica* (sunt)

*Acacia nilotica* is a widely spread species in the northern part of tropical Africa. It grows on heavy black or dark grey alkaline clay in riverain basins or in areas that are periodically inundated. There are many small forests of *Acacia nilotica* along the Blue Nile in the Blue Nile and Senar states. These forests are managed for the production of railway sleepers. Sunt is a hard and heavy timber, with specific gravity of about 0.8 at 12% moisture content. It has an attractive red warm appearance. Heartwood is red and contains a lot of of extractives and deposits. Sapwood is dirty white and contains less extractives and deposits (Vogt 1995). The timber is difficult to saw and machine, but it planes and turns well. It would make very attractive bowls, toys, images, and other items. It would also make handsome but rather heavy furniture (Anonymous 1968).

### Table 2.2 Chemical composition of cotton stalks

<table>
<thead>
<tr>
<th>Component</th>
<th>Particle size in mm</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fine fraction</td>
<td>Coarse fraction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.1-0.5) mm</td>
<td>(0.5-1.0) mm</td>
<td></td>
</tr>
<tr>
<td>Lignin %</td>
<td>21.3</td>
<td>23.4</td>
<td></td>
</tr>
<tr>
<td>Pentosans %</td>
<td>18.5</td>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td>α– cellulose %</td>
<td>43.5</td>
<td>45.2</td>
<td></td>
</tr>
<tr>
<td>Ash %</td>
<td>5.7</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>Moisture %</td>
<td>6.7</td>
<td>6.3</td>
<td></td>
</tr>
</tbody>
</table>

2.2.2. Binding materials

Binding or adhesive materials have been produced from natural, synthetic and inorganic sources. The advent of synthetic resins had paved the way for the production of viable panels. Synthetic adhesives can be classified into thermosetting and thermoplastic adhesives (Rowell, *et al.* 1993). Thermosetting resin systems for timber are usually based on
formaldehyde. Thermoplastic adhesives as far as timber is concerned are based on poly vinyl acetate (Dinwoodie 1996). Thermosetting adhesives harden by heat. Their bonding is irreversible. Thermoplastic adhesives are high polymers which melt or soften when heated and re-harden when cooled (Kollmann 1975).

For the production of particleboard made of annual plant residues, mainly urea-formaldehyde or urea-melamine formaldehyde are used. In recent years gypsum and cement are also used. A new binding material—the polycondensation product of urea borates and urea phosphate with silicates has been formulated (Kozlowski et al. 1994).

Binders for particleboard which are available in the market include urea formaldehyde, phenol formaldehyde, melamine–urea formaldehyde, isocyanates, tannin formaldehyde and cement (Mohamed 1989).

2.2.2.1. Cement

Ordinary Portland cement which is used as a binder for particleboards is one of the cement types which set by hydration. It consists of tricalcium silicate 3CaOSiO₂ and dicalcium silicate 2CaOSiO₂ and some minor proportions of tricalcium aluminate 3CaOAl₂O₃ and tetracalcium alumino-ferrite 4CaOAl₂O₃Fe₂O₃. Cement properties vary depending on the original mixtures of limestone and clay which are fused and pulverized, usually with small amounts of gypsum (Wills 1965). The chemical and physical properties of commercial Portland cement (type 1), produced by AL-Amriya Cement Company-Egypt, as compared to ASTM specifications C-150 are presented by Nasser 1996 as shown in Table 2.3.
Table 2.3 Chemical composition and physical properties of Ordinary Portland cement made by Al-Amriya Cement Company, Egypt

<table>
<thead>
<tr>
<th>Component</th>
<th>Composition (%Wt.)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ASTM (C 150)</td>
<td>Cement used</td>
</tr>
<tr>
<td><strong>Chemical analysis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silica (Si₂)</td>
<td>-</td>
<td>20.18</td>
<td></td>
</tr>
<tr>
<td>Alumina (Al₂O₃)</td>
<td>-</td>
<td>5.26</td>
<td></td>
</tr>
<tr>
<td>Ferric Oxide (Fe₂O₃)</td>
<td>-</td>
<td>4.29</td>
<td></td>
</tr>
<tr>
<td>Calcium Oxide (CaO)</td>
<td>-</td>
<td>61.60</td>
<td></td>
</tr>
<tr>
<td>Magnesia (MgO)</td>
<td>Max. 6.0</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Sulfer Trioxide (SO₃)</td>
<td>Where C₃A ≤ 8</td>
<td>Max. 3.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Where C₃A ≥ 8</td>
<td>Max. 3.5</td>
<td>2.14</td>
</tr>
<tr>
<td><strong>Main components</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tricalcium Silicate (3CaOSiO₂)</td>
<td>-</td>
<td>49.83</td>
<td></td>
</tr>
<tr>
<td>Dicalcium Silicate (2CaOSiO₂)</td>
<td>-</td>
<td>20.26</td>
<td></td>
</tr>
<tr>
<td>Tricalcium Aluminate (C₃A)</td>
<td>-</td>
<td>6.68</td>
<td></td>
</tr>
<tr>
<td>Tetracalcium Aluminoferrite (C₄AF)</td>
<td>-</td>
<td>13.05</td>
<td></td>
</tr>
<tr>
<td><strong>Physical properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time of set (Vicat test method)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial (min.)</td>
<td>Min. 45</td>
<td>195</td>
<td></td>
</tr>
<tr>
<td>Final (min)</td>
<td>Max. 375</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>Compressive strength(Kg/Cm²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 days</td>
<td>Min. 197</td>
<td>253.57</td>
<td></td>
</tr>
<tr>
<td>14 days</td>
<td>-</td>
<td>274.75</td>
<td></td>
</tr>
<tr>
<td>21 days</td>
<td>-</td>
<td>301.21</td>
<td></td>
</tr>
</tbody>
</table>

(Analyzed and tested at the Faculty of Engineering, Alexandria University, Egypt).
2.2.2.2. Urea formaldehyde

Urea formaldehyde adhesives are the first choice of chipboard manufacture for three main reasons; they are easy to use, they are cheap and the quality of board is highly satisfactory for most current applications (Rayner 1968). Urea formaldehyde resins are non flammable, have good thermal properties, hardness, colorless and easy adaptability to different curing conditions (Pizzi 1983).

Urea adhesives are a condensation product of urea and formaldehyde. The reaction between the two chemical compounds is very complex and it produces both linear and branched polymers, and a tridimensional network as well, when the resin is cured (Pizzi 1983). Urea formaldehyde normally requires the addition of a hardening agent to initiate the final stage of curing (Rayner 1965). These hardeners are either acidic or capable of liberating acid when mixed with the adhesives (Moslemi 1974). Solutions of ammonium salts, generally ammonium chloride with urea are used as hardeners (Pizzi 1983).

2.3. Mineral-Bonded Products

Mineral-bonded wood particle composites are moulded panels that contain 10-70 percent of its weight, wood particle and 30-90 percent mineral binder. Mineral binders are Portland cement, magnesia cement, gypsum and mixed mineral binders of at least two components of the above mentioned binders or an accelerator (Ishihara, 1996). Wood wool slabs using magnisite as a binder were first produced but later Portland cement was introduced (Dinwoodie and Paxton 1983). The most important one is cement because of its high quality and availability virtually all over the world (Malony 1989).
The commercial production of boards by combination of wood and mineral binders dates back to the early nineteen thirties. Early attempts to produce cement bonded particleboards were not very successful. The boards were very heavy, with low strength properties particularly resistance to impact (Dinwoodie and Paxton 1983). The production of dense particleboards, with good properties, using cement as a binder, started in 1962 in U.S.A. and in 1966 in Switzerland (Dinwoodie 1979). Successful products of light weight are being made all over the world (Malony 1989).

Properties of the composites are significantly affected by the matrix and also the chemical properties of the raw wood and density of the composites.

These composite panels are commonly used as roof decking, siding, or sheathing because of their sound-absorbing, fire resistive properties, and high dimensional stability. Medium density panels can be used in doors, floors, load bearer walls, partitions, concrete forms, and exterior siding (Ishihara 1996).

A unique feature of mineral bonded composites is that their manufacture is adaptable to different levels of technology. In addition, no heat is required to cure the panels. For instance, cement-bonded particleboards are fabricated in the Philippines mostly by manual labor and are being used in low cost housing, whereas in Japan, the fabrication of these composites is automated and they are used in very expensive modular housing (English et al. 1997).

2.3.1. Types of cement bonded products
There are different types of mineral-bonded products; wood-wool, building blocks, cement-bonded flakes or particleboards and cement bonded fiber boards;
2.3.1.1. Wood-wool cement boards

These are boards manufactured from long shavings of wood mixed with cement. The early light weight boards were known in Europe under the name ‘Heraklith’ and in North America as ‘Excelsior’ boards (Dinwoodie and Paxton 1983). The first excelsior boards were produced in Radenthein, Austria, in 1914 and these were bonded with magnesite (John 1999).

The first cement bonded boards, were produced in 1928. In Germany, the binding agent used before world war II was a mixture of cement, magnesite and gypsum with ratios of 39 %, 35 % and 26 % respectively, (Maloney 1989). After the war cement became the dominant binder in Europe. The technologies of the processes have been highly developed and the properties were standardized.

Wood wool cement board is a universal material. It can be produced in high-technology plants as well as smaller local plants. The manufacture of wood wool cement requires particles with specific and defined dimensions; length ranges between 25-500 mm, width ranges between 0.5-5 mm and thickness between 0.03-0.64 mm (Mallory 1989).

The shredded wood is then treated with a salt solution (e.g. CaCl₂) and mixed with Portland cement in a 1: 2 ratio based an oven dry weight. The mixture can be spread onto plywood or metal moulds solid conveyors or belts and stacked. The mats are then pressed at room temperature under a pressure of about 10 pounds per square inch (psi.). The stack is clamped under pressure for about 24 hours and then removed from the moulds and cured for 2-4 weeks. The boards are then trimmed and finished (Anonymous 2001).

There are different systems used to press the boards; in early days the mat of product is pressed by concrete weight and this pressure is kept for about 25 hours, with technological development, the duration of pressing
Board density ranges between 160 to 600 Kg/m³ and those ranging between 140 and 420 Kg/m³ are considered to be an ideal for most constructional uses. Board thickness generally ranges from 25 to 80 mm (Moslemi 1974).

2.3.1.2. Cement- bonded particleboard

Wood cement particleboard which is available under a range of brand names; Century Board, Duripanel, Falgurit Cemchip, Tacpanel and Cemboard has evolved as a high density smooth surfaced boards with promising characteristics for exterior use or where fire resistance is needed.

Heavy weight wood cement boards were developed by the Elmendorf Research Inc. in America (Stillinger and Wentworth 1977). The concept of a high-density board using chips was taken up and developed in Switzerland with slight modifications. After successful tests at official laboratories, both in Switzerland and in Federal republic of Germany an automated wood-cement board plant was built by Bison-Werke, a German supplier of particleboard plants. Cement bonded particleboard established itself in Switzerland and central Europe in mid-1970s (Dinwoodie 1996). Cement Bonded particleboard differs from wood wool cement board in that the wood is in particle rather than strand form and the finished boards are usually much wider and pressed to a higher density of about 1250 kg per cubic meter. The production of such boards generally requires higher technology equipment since the boards are required to comply with strict international standards concerning their bending strength properties and thickness tolerances (Anonymous 2001). The manufacture of cement bonded particleboard requires careful selection of the wood raw materials because wood extractives or
hemicelluloses have an unfavorable effect on the cement. The logs are
debarked and then stored for at least three months to reduce their
moisture and sugar content. The selected species are reduced to flakes
using drum knife flaking machines and hammer mills as for conventional
particleboards. The wood particles are of dimensions 10 – 30 mm in
length and 0.2 – 0.3 mm thickness (Dinwoodie and Paxton 1983,
Anonymous 2001). The particles are then screened and separated into
surface and core materials.

A mixture of Portland cement, wood and water is made in the ratio 3:1:1
of the respective components. Water evaporation is monitored constantly
and the volume of water added to the mix is adjusted accordingly. Small
quantities of chemicals such as calcium chloride is also added to the
mixture to assist cement setting quickly. The mixed furnish is fed to the
forming machine which spreads a continuous mat of uniform thickness
onto a conveyor driven series of caul plates moving at uniform speed.
The constant pouring and conveyor speeds guarantee a mat of uniform
thickness. The mat is subsequently cut into lengths of the same size as the
caul plates. The mats are then stacked and compressed at a pressure of
about 2.4 N /mm² to one third of its original thickness over a period of 2-3
minutes (Dinwoodie and Paxton 1983, Anonomous 2001).

The mats are clamped and heated in a chamber at 70 – 80 °C for 6-8
hours to allow the cement to harden. Work is underway at the present
time to reduce the curing time. Rapid curing of cement bonded
particleboard by applying steam-injection pressing and incorporation of
certain cement setting accelerators such as sodium hydrogen carbonate
(NaHCO₃), Sodium silicate (Na₂SiO₃) and magnesium chloride (MgCl₂)
has been of interest in recent years (Kawai 1995). Care must be exercised
in adding substances to speed up the setting of cement. Such substances
can not be used in quantities, which impair the board properties (Maloney 1989). The clamps are then removed and the panels are stacked for 12 to 18 days for maturing (TRADA 1985). The boards are further dried and conditioned to equilibrium moisture content prior to finishing and shipment.

2.3.1.3. Building blocks

Building blocks using cement as a binder for wood particles have been used for many years. This type of product has been popular in Scandinavia. A number of buildings have been made with this type of material in the United States. A pilot plant has been built in Spokane, Washington, where the blocks are fabricated by machine. The sizes of the boards produced are about 203 mm thick, 305 mm high and 1.21 m long. The machines can produce larger blocks with desirable heights and thickness. Also, tongued and grooved blocks can be made for the do-it-yourself builder. The large size blocks weigh approximately 45.5 kg and compare favorably to the weight of a similar pieces of wood of about the same size. The blocks have excellent insulation properties. Most of its working properties such as nailing, sawing, drilling and sanding are much like any piece of soft wood. Because of the ease in manufacturing, this type of building block is not only suitable for some operations in developed countries but it is an excellent product for production in developing countries (Mallony 1989).

2.3.1.4. Cement bonded fiber board

The manufacture of cement bonded wood fiber board is similar to that of cement bonded particleboard and the terms are sometimes used interchangeably. In the case of cement-bonded fiber boards the wood is defibrated rather than smaller pieces of wood or particles with a moisture content of about 12-16 \%. 
Additives such as silica, sizing agents and binders can be mixed with water and the pulped cellulose fibers. Much of the water is then removed and the mixture is formed into mats, cut to size or molded (Anonymous 2001).

2.4. Properties of Particleboard

There are many factors, which affect the properties of particleboard. Among the major factors that affect the properties of particleboard are the types of raw material. This is covered by type and size of particles, type and amount of binder, additives used, mat moisture distribution, mattress structure, board specific gravity and orientation of particles. Almost all of these parameters interact with each other.

Methods of testing the properties of particleboard have been published in all major particleboard producing countries. The International Organization for Standardization (ISO) has also released standard test methods. Kollmann et al. (1975) outlined the properties that may be tested including several physical, mechanical and other technical properties.

Cement-bonded particleboards, comprising by weight about 70-75 percent Portland cement and 20-30 percent wood chips, the boards are heavy with a density of about 1200 kg/m$^3$. However, the use of this amount of cement imparts some very significant bonuses to the performance of the boards produced; these can be summarized as:

1. The high degree of alkalinity (pH of 11) ensures immunity against fungal attack.
2. Cement reduces very appreciably the dimensional movement of wood chips in the presence of moisture.
3. The high content of cement results in panels with very good resistance to spread of flame; and
4. The high density of board ensures poor sound transmission.
Cement-bonded particleboards should be viewed not as a competitor to resin-bonded chipboard, but as complementing its use by extending the application of the so-called particleboards into hazard areas where there is a risk of moisture, fire or high noise levels (Dinwoodie 1996). In the United Kingdom the material is specified in BS 5669: Part 4. The values for bending strength and impact resistance were found very much lower and values for internal bond slightly lower than those for type C₄ chipboard (a grade mainly used for flooring). The stiffness of the board (modulus of elasticity), its dimensional stability with changing relative humidity, and its resistance to moisture were far superior to those of type C₄ chipboard. The values in the new draft European standard and pr EN 622-2 are similar to those in BS 5669: Part 4. Its external performance, even in an uncoated form, is far superior to that of chipboard and OSB, with strength values after seven years' exposure above the original unexposed strength (Dinwoodie 1996).

2.5. Product Applications

Wood-cement boards have shown positive results as building materials for applications since the Bison wood-cement panels. They are virtually incombustible, with high resistance to water and humidity absorption can easily be motioned, durable against decay and termites and the surfaces are suitable for multipurpose treatment (Stilling and Wentworth 1977).

The following are some of the many suitable applications for the product:

1. Pre-Fabrication (pre-Fab) manufacture.
2. Low-cost housing.
3. Mobile homes.
4. Schools.
5. Industrial buildings.
6. Agricultural buildings.
7. Commercial buildings.

European experience has demonstrated the successful application of wood cement particleboard for cladding, internal wall lining and flooring, agricultural use (especially stock rearing pens) and for sound absorption barriers. Additional applications have been identified such as for dove, ventilation ducts and refuse shafts, fire resistant stiffening for panes, and soffits (Dinwoodi and Paxton 1983). Other uses have included ceilings, overlayments of old floors in building refurbishment and as a core board for factory-applied finished cladding panels (Dinwoodie 1996).

2.6. The Compatibility of Cement and Wood

The ability of wood to combine with Portland cement is termed wood compatibility. When cement is mixed with water, its constituents undergo a series of chemical reactions, which are responsible for cement hardening or setting. These reactions are designated hydration and the solids formed are referred to as hydration products.

When wood particles are mixed with Portland cement paste and allowed to harden, a composite is formed. One problem that limits the development of cement bonded panel is the low level of wood-cement compatibility. This is due, up to a degree, to natural incompatibility existing between wood as an organic material and cement, an inorganic binder. Softwoods are generally more compatible with cement than hardwoods. Several researchers indicated that, wood extractives are responsible for this incompatibility problem (Sandermann et al.1960, Bibilis and Lo 1968, Moslemi et al. 1983, and Liu and Moslemi 1985).

Chemical and physical interactions that affect the bonding between wood and cement are poorly understood at present. The mechanism of retardation to cement setting by organic substances was explained as adsorption (Bugrina et al. 1968). The carboxylic group can be adsorbed
on the surface of tricalcium aluminate and tricalcium silicate of cement, to form a layer on the grain which interrupts the water supply into the core of the grain. Also the hydroxyl groups in the carboxylic acids are considered adsorption groups. With organic admixtures, hydration of tricalcium aluminate is hindered seriously at the early stages of hydration, but silicates and ferrites are affected to a lesser degree (Moslemi and Pfister 1987).

Simple sugars in wood migrate during drying to the surface. Since these sugars contain hydroxyl and carboxylic functional groups, they may complex with calcium, aluminum and iron in cement and retard (Young 1970) and perhaps disrupt (Mariampol's 1974) the crystallization reactions.

Wood components may also be solubilized and or degraded by calcium hydroxide which is formed during cement hydration. This calcium hydroxide which is produced in the initial cement setting results in an alkaline cement paste (pH =12.5). Hemicelluloses are non crystalline and alkaline soluble, so they may dissolve in the cement paste and affect cement setting. In addition, hemicelluloses may undergo peeling reactions and form inhibitory sugar acids (Fischer et al. 1974). The acetyl groups present in the hemicelluloses may also be cleaved by the alkali to form potentially inhibitory metal acetate compounds. Since xylans are high in acetyl contents and are the predominant sugars in the hemicelluloses of hardwoods, this alkaline hydrolysis may be a major reason for the incompatibility of many hardwoods with cement (Browning 1976 Goldstein 1984). It is believed that some compounds form a film around the cement particles and therefore inhibiting or entirely obstructing the crystalline formation essential to strength development (Fisher et al. 1974, Logvinенко et al.1976, Yamagishi et al. 1982).
Non-polar extractives such as resins, fats and terpenes may also migrate during drying to the wood surface and form a hydrophobic surface layer. This layer may hinder hydrogen bonding between wood and cement and thus weaken the bond strength. Phenolic compounds such as tannins can also combine with metal ions in cement and inhibit normal hydration reactions (Bash and Rakhimbaev 1973). Miller and Moslemi (1991a) studied the effect of model compounds representing classes of wood components. They concluded that all hydration characteristics were substantially affected by sugars, tannins and hemicelluloses, with tannins and hemicelluloses having the greatest effect.

2.6.1. Methods of compatibility evaluation

Hydration reactions are all exothermic, that is to say, they liberate heat. The rate of heat evolution is an important quantity (Mindess and Young 1981). Compatibility can be measured by testing the exothermic behavior during the hydration process or by measuring some strength properties of wood–cement mixtures. Sandemann and Cohler (1964) classified the species studied on the basis of maximum hydration temperature. Species having maximum hydration temperature above 60 °C as "suitable", species with temperature between 50°C and 60°C as "suitable under limited conditions", and species with temperature lower than 50 °C "unsuitable".

Weatherwax and Tarkow (1964) developed an inhibitory index (I) based on the time to reach the maximum hydration temperature between neat cement and wood cement mixture as indicated by the following equation:

$$I = \left( \frac{(t_2-t'_2)}{t'_2} \right) \times 100$$

Where

I = Inhibitory index (%).
\( t_2 \) = time to reach maximum hydration temperature of wood cement mixture.

\( t'_2 \) = the time to reach maximum temperature of neat cement.

Hofstrand et al. (1984) incorporated maximum temperature and the maximum slopes of the temperature curve (s and \( s' \)) of the wood–cement and neat cement, respectively, into the calculations of an index value (I). The equation will then be as follows:

\[
I = \left[ \frac{(t_2 - t'_2)}{t_2} \right] \left( \frac{T'_2 - T_2}{s' - s} \right) \times 100
\]

Where \( T_2 \) is the maximum temperature of wood-cement, and \( T'_2 \) is the maximum temperature of neat cement.

Hachemi et al. (1990) established and compared three techniques for the evaluation of wood cement compatibility. Several hydration characteristics were measured to develop the three classification methods. These characteristics included the maximum temperature, time to reach this maximum, mass of each mixture component, and the area under the hydration curve.

Hydration behavior can be characterized by the weighted maximum temperature rate ratio to calculate the compatibility factor \( (C_T) \) as shown with the following equation:

\[
C_T = \left( \frac{R_T}{R'_T} \right) \times 100
\]

Where: \( R_T \) is the weighted maximum hydration rate of wood cement and is expressed in °C / h as shown in the equation below:

\[
R_T = \frac{T_2}{t_2} \left( \frac{m_w + m_1}{m_c} \right)
\]

Where:

\( T_2 \) = maximum temperature.

\( t_2 \) = time to reach this maximum.
\( m_w = \) mass of water including wood moisture content.
\( m_i = \) mass of dry wood.
\( m_c = \) is the mass of cement.

\( R_T = \) the weighted maximum temperature rate corresponding to the neat cement mixture.

But it should be noted that different cements give different hydration characteristics.

The second method used by Hachimi et al. (1990) to characterize compatibility, is the heat rate ratio \( (C_H) \) which is expressed by the following equation:

\[
C_H = \left( \frac{R_H}{R_{H\prime}} \right) 100
\]

And \( R_H = \{(T_2 - T_r)\left[ (mc)_w + (mc)_1 + (mc)_c + (mc)_d \right] \} / t_2
\]

Where:
\( T_r = \) room temperature;

\( (mc)_w, (mc)_1, (mc)_c, (mc)_d \) are thermal capacity (Kcal / °C) of water, wood, cement and Dewar flask, respectively.

The compatibility between wood and cement can be characterized by the compatibility factor \( C_H \) which is the ratio of the maximum wood cement heat rate \( (R_{H \prime}) \) to that of cements \( (R_{H \prime}) \). The third method used by Hachimi et al. (1990) is the area ratio method. Cement hydration behavior shows a rapid evolution of heat over a short period, followed by a dormant period then followed by hardening stage. The same behavior is shown by wood-cement water mixture; except that the hydration rate is generally lower than that of neat cement beyond the initial setting time.

Since the hydration period between the initial setting times for cement tested (3.5 and 24 hours) is the most important stage when considering the neat cement hydration. The area \( (A_{nc}) \) under its hydration heat rate
curve would be an indicator of cement hydration behavior. The 24 hour limit was chosen for practical reasons in order to limit hydration test duration. The area under hydration heating rate curve for wood–cement-water mixture ($A_{wc}$) would also characterize the hydration behavior of the species used in the mixture. Therefore, the compatibility of any lignocellulosic material could be determined using the compatibility factor $C_A$, which is the ratio of the areas as shown in the following equation:

$$C_A = \left( \frac{A_{wc}}{A_{rc}} \right) \times 100$$

Hachimi et al. (1990) concluded that the ($C_A$) factor appears to be the best wood species ranking method used. It provides comparison data among highly inhibitory species. They recommended that this method is to be used as a standard method for classification.

Hachimi et al. (1990) mentioned that hydration characteristics have been commonly used to assess the compatibility with cement for potential lignocellulosic materials. Nasser (1996) studied the compatibility of four species and stated that regression analysis of his results indicated that both hydration and compressive characteristics of wood cement mixture can be used as suitable estimates. Since cement-bonded wood products are used primarily for structural applications, it is logical to use strength properties as indicators of compatibility. Compressive strength of wood cement molds are widely used to measure compatibility. Other research workers used tensile strength of wood cement molds and bending strength of wood cement boards for compatibility evaluation (Lee and Hong 1986, Moslemi and Pfister 1987, Lee et al. 1987, Badejo 1989, Lee and Short 1989, Miller and Moslemi 1991, Lee and Hse 1993, and Blankenhorn et al. 1994, Abdelgadir and Ibrahim 2002).

2.6.2. Factors affecting compatibility
The effect of wood on cement is governed by a number of factors which include felling season, geographic location and the presence of bark and decayed wood (Sanderman and Kohler 1964). The effects of other factors such as wood species, cement to wood ratio, extractives and chemical additives are highlighted below:

2.6.2.1. The effect of wood species

Yashiro et al. (1968) studied the manufacturing conditions of cement bonded wood boards of *Larix leptolpis*, *Betula japonica*, and *Ptercarya rhoifolia* and concluded that the temperature of wood-cement mixture attained, varied with the species and between sapwood and heartwood.

Kamll and Suwandi (1974) found that *Dipterocarpus graeilis*, *Shorea javanica* and *S. leprosula* were good and *Anthocephalus cadamba* (sapwood) was fair, while the heartwood of *Anisoptera marginata*, *Hopea mengarawan*, and *Vatcea spp.* were poor with regard to their suitability for wood wool cement boards.

Paribotro et al. (1977) investigated the suitability of five Indonesian wood species for wood–wool cement boards and cement-bonded particleboard based on maximum hydration temperature. They found that *Cananga odorata*, *Ilex pleibrachiata*, *Manglietia glance* and *Sloanea signum* were good while *Gossampinus malabarica* was fair.

Hofstrand et al. (1984) studied the effect of nine timber species from Northern Idaho, U.S.A, on cement setting. They concluded that wood cement water mixtures are highly species sensitive.

Some wood species produce excellent boards with Portland cement, while other similarly manufactured fall apart upon simple handling. The cause of such board inconsistencies is thought to be the soluble carbohydrates and phenolic substances of the wood.

such as maximum temperature, time to reach maximum temperature as well as inhibitory index. Their study indicated that, chestnut oak (*Quercus prinus*) was the least inhibitory and can be used for board making without treatment, while red maple (*Acer rubrum l.*) was the most inhibitory.

Jain et al. (1989) in his study of some softwoods, hardwoods and other lignocellulosic materials including agrowaste, concluded that among the softwoods beside others, *Pinus wallichiana* and *Picea smithiana* are suitable; some of the hardwoods such as *Eucalyptus camaldulensis*, and *Terminalia paniculata* are compatible with cement. Among the agricultural residues studied, rice husk-cement mixtures developed adequate strength.

Young and Moslemi (1984) investigated the effect of hot water extraction treatment and the addition of accelerators on the inhibitory index of 8 Korean lignocellulosic materials. They found that the inhibitory index of *Pinus densiflora* and *Pinus rigida* were suitable under limited conditions for composites without any treatment. They also found that 6 of the 8 lignocellulosic materials reached a maximum hydration temperature of less than 50 °C. These species were suitable under limited conditions. They concluded that none of the species studied could be classified as highly suitable.

Lee (1985) compared the insulation and bending properties of cement – bonded cypress (*Taxodium distichum*) excelsior boards with southern pine excelsior boards. His conclusion was that cypress excelsior boards can meet all commercial standards and possess the same bending properties of southern pine excelsior boards.

Lee and Hong (1986) stated that the compressive strength of wood and cement mixtures depends primarily on the wood species used. They
presented a simple compression test of cylindrical samples as indicator of wood cement compatibility. They indicated that compressive strength was linearly proportional to the maximum hydration temperature, but independent of hydration time. They found that maximum hydration temperature ranged from 30 °C to 33 °C for green wood and 32 to 51 °C for air-dried wood. The highly significant difference in hydration temperature was attributed to species effect. Sutingo and Sulastiningsih (1986) classified the suitability of 73 wood species for wood cement boards using the hydration test developed by Sandermann et al. (1960), and the three temperature classes of Nizar Kamil in Indonesia (41 °C and up was good, 36 to 41 °C was medium and less than 36 °C was poor quality). They found that 61 wood species were good, six wood species were medium and six species were poor or bad quality.

Tachi et al. (1988) made cement-bonded particleboards from four species of Malaysian fast growing trees and from Japanese hinoki. They found that boards from Albizia falcate and Gmelinia arborea had nearly equal bending strength to those from Japanese hinoki, but Eucalyptus deglupta gave only 70 percent of the strength of the boards from hinoki. Abdul Kadir and Sudin (1989) indicated that fresh rubber wood was unsuitable for wood-cement boards. They discovered that the carbohydrates could be easily reduced by natural storage in an open area for several weeks.

Manzanares et al. (1989) investigated the suitability of three species, namely, Casuarina equistifolia, Pinus tropicalis and Bursera simaruba, by measuring the hydration temperature. They found that C. equistifolia was very suitable, P. tropicalis was suitable and B. simaruba was unsuitable. Yasin and Qureshi (1989) studied eight hardwood species and
indicated that poplars wood (Populus spp.) provide a better raw material for wood-cement boards than Acacia nilotica, followed by Dalbergia sisso, and Tamarix aphyla. Among the poplars, P. alba was better than P. deltoids, P. cilicata and P. euphratica.

Hashimi and Moslemi (1989) studied sixteen Moroccan wood species and concluded that species may have the same extractive content but different compatibilities with cement. This indicates that the chemical composition of the extractives also has an impact on compatibility. A number of researchers have shown that differences in behavior of species when mixed with cement are due to differences of cell wall substances (Biblis and Lo 1968, Moslemi et al. 1983, Hofstrand et al. 1984, Lee et al. 1987, Kumar 1980, Jain et al. 1989, and Hachmi et al. 1990).

Hachimi et al. (1990) studied nine hardwoods and softwood species for their compatibility with cement. Among the species studied Pinus contorta var. latifolia was the most compatible with $C_A = 85\%$ while Argania spinosa was the least compatible with $C_A = 9\%$.

Miller and Moslemi (1991a) examined the effect of species on hydration and tensile strength of wood–cement mixtures. They concluded that hardwoods adversely affected both splitting tensile strength and exothermic behavior of cement more than softwoods.

Lee and Hse (1993) evaluated cement-excelsior boards made from yellow poplar, sweet gum, and southern pine and sweet gum and southern pine mixture. They found that the properties of the boards made with yellow poplar were equal to or better than those made with southern pine. The properties of boards made with all sweet gum or 50% sweet gum and 50% southern pine did not meet the requirements of bending strength. They also found that sweet gum generated a stronger inhibitory reaction with cement. Oyagade (1994) examined the compatibility of some Nigerian species with ordinary Portland cement and observed
considerable differences between the species. *Gmelina arborea* was the most inhibitory to cement setting among the species examined. Ibrahim (1995) studied the effect of five wood species grown in Sudan and observed that the species effect is significant. The most inhibitory species was *Acacia nilotica* and the least was *Eucalyptus camaldulensis*. Nasser (1996) studied the compatibility of wood-cement mixtures of four wood species, using hydration and compressive strength tests. He found that Poplar (*Populus spp.*.) and European red wood (*Pinus sylvestris*) showed the highest values, while the lowest were obtained by *Casuarina gluca* and *Eucalyptus camaldulensis*. He concluded that poplar and European red wood can be used for cement panels without any treatment and chemical additives and are suitable under limited conditions, while *Casuarina* and *Eucalyptus* need some treatments. Moursi (2002) stated that hydration characteristics and compressive strength tests revealed that cotton stalks had low level of compatibility under untreated conditions.

2.6.2.2. Effect of wood Extractives

It has been known for a long time that nearly all woods affect the rate of cement setting to a greater or lesser degree. At the worst this may produce so poor results as to make the product useless. Farmer (1967), Deppe (1975) and Hofstrand *et al.* (1984) indicated that, the inhibitory effect of wood was attributed to the presence of different types of the extraneous materials present in the wood. Sandermann *et al.* (1960) studied the effect of wood extractives of spruce and beech on the setting of cement-bonded wood materials. They found that cement had a hydration temperature higher than 80 °C but after addition of glucose it was 28 °C and it was higher than 60 °C with spruce while with beech wood it was higher than 27 °C. Bugrina *et al.* (1968)
studied the effect of spruce extractives on the hydration and hardening process of cement. He found that addition of less than 0.1% of these substances, significantly retarded cement hydration. With the addition of higher than 0.1%, the hydration was almost discontinued.

Previte and Grace (1970) investigated the effect of various saccharide compounds on the hydration of Portland cement, using isothermal calorimetry. They indicated that set retardation efficiency of saccharide compounds was related to molecular weight and the stability in the alkaline aqueous phase of hydrating cement.

Stephen et al. (1974) studied the interaction of some components of wood-cement mixture by using the Infrared (IR) spectra of CaCl₂ mixtures with equal weights of glucose, xylose, or arabinogalactan. They concluded that wood which contains high concentrations of such sugars, were not suitable.

Choi et al. (1984) investigated the effect of monosaccharides extracted by saturated Portland cement solution, on cement setting by using the inhibitory index of some wood species widely reforested in Korea such as Pinus koraiensis, Pinus rigida, Pinus densiflora and the agricultural waste of rice husks and rice straw were used. They concluded that the inhibitory index increased with increasing the ratio of the hexoses to pentoses.

Liu and Moslemi (1986) stated that water soluble wood extractives play a dramatic role in cement setting. Even small amount of extractives can be detrimental to cement hardening and the subsequent development of strength properties of cement bonded composite boards.

Experiments have shown that almost all simple sugars examined and also some other carbohydrates bring about a complete loss in strength of the cement when added in amounts as low as 0.25% by weight of cement. Sudin and Ibrahim (1989) reported that the amount of sugars in wood is
an important factor, because above a critical value, identified to be 0.5 to 0.6 % (Artuor 1988) cement setting is inhibited.

Tannins produce a similar effect (Milestone 1977, Miller 1987). Other phenolic compounds examined such as quinones as well as the polyhydric alcohols are much less effective (Farmer 1967). It has been shown that the heat of hydration of cement is reduced in the presence of sugars and this may be taken to indicate that hydration is prevented by some kind of barrier. It is believed that these compounds form a film around cement particles and hence hinder crystalline formation essential to strength development (Farmer 1967, Fisher et al. 1974, Logvinenko et al. 1976, Yamagishi et al. 1982).

Hachimi and Moslemi (1989) studied the correlation between wood-cement compatibility and wood extractives using nine hardwood and softwood species. They indicated that different woods may have the same extractive content but different compatibility with cement. Miller and Moslemi (1991 b) studied the effect of model compounds on hydration characteristics and tensile strength. They concluded that models compounds representing cellulose, lignin, fatty acids and terpenes at 1.0 % or less did not significantly decrease tensile strength. Glucose caused the greatest decrease in tensile strength. All hydration characteristics were substantially affected by sugar, tannin and hemicelluloses, with tannin and hemicelluloses having the greatest effect.

2.6.2.3. Effect of cement/wood ratio

An earlier study by Prestemon, (1976) indicated that wood cement boards, made from wood slivers, sawdust, and cement had a higher mechanical strength when the cement / wood ratio was increased from 3/4 to 3/2. Bahre and Greten (1977) indicated that commercial wood cement panels incorporating 2.75 to 3.0 parts of Portland cement to 1.0
part of wood particles (weight basis) are reported to attain acceptable physical and mechanical properties.

Lee (1984) stated that if a lower cement/wood ratio is used, wood excelsior will not receive adequate cement coating, which results in poor bonding. If a higher cement/wood ratio is used, the compaction ratio will be reduced, resulting in lower bending strength. Lee and Hog (1986) reported that lower cement to wood ratios can be used when identifying suitable species under the influence of calcium chloride as an accelerator. Pfister and Moslemi (1986) studied the effect of cement/wood ratio and cement type on bending strength and dimensional stability of wood–cement composites. They found that decreasing cement to wood ratio from 3:1 to 1.5:1 increased modulus of rupture (MOR) from 15.1 MPa (155Kg/cm²) to 16.3 MPa (166 Kg/cm²) for type I cement (ordinary Portland cement), and from 14.8 MPa (150.9 Kg/cm²) to 16.4 MPa (167.2 Kg/cm²) for type III cement (High early strength Portland cement). Modulus of elasticity decreased from 5.35 MPa (54.5 Kg/cm²) to 3.6 MPa (36.7 Kg/cm²) for type I cement and from 5.34 MPa (54.4Kg/cm²) to 3.47 MPa (35.3 Kg/cm²) for type III cement when the cement/wood ratio decreased from 3:1 to 1.5:1.

Lee et al. (1987) concluded that decreasing cement/wood ratio will result in a reduced hydration temperature, compressive strength and prolonged hydration time.

Moslemi and Pfisler (1987) stated that the economics of wood-cement composites technology may become more favorable if the proportion of cement in cement-wood panels can be reduced without significantly impairing properties. This will lower the weight of the panel and would result in cost effectiveness by decreasing the percentage of cement and thus increasing the less expensive lignocellulosic materials.
Cement/wood ratio is an important manufacturing process variable which tends to predominate in influencing the final density of the board. The effect of cement/wood ratio was very important in determining the bending strength when Oyagade (1989) compared boards prepared at varying cement to wood ratios.

Generally, the strength properties of cement-bonded particleboards increase with increase in the proportion of cement in the wood cement mixture. It seems that only the cement bonded particleboards produced without chemical additives at wood: cement ratio of 1:3 could satisfy the Malaysian standard requirements. Sudin and Ibrahim (1989) stated that cement and wood are usually mixed by weight at the ratio of two parts cement to one part wood (oven dry bases) for cement-bonded excelsior boards.

Blankenhorn et al. (1994) investigated the effect of hydration time, mild chemical modification, and cement to wood ratio (from 13.3:0 to 13.3:5.5 by weight) on compressive strength of hardwood–cement composites. They found that as hydration time increased, the compressive strength increased. They also found that increasing the amount of hardwood furnish above the ratio of 13.3:2 was unsuccessful.

Oyagade et al. (1995) reported that veneer laminated cement-bonded particleboards were stronger and stiffer with increased cement/wood ratios and density.

Ibrahim (1995) reported that untreated compression cubes made from a mixture of cement and Acacia nilotica wood failed to set at lower cement/wood ratios (2 and 4) and did not gain the minimum value for building bricks (7 N/mm²) in all ratios used.

John (1999) reported that inorganic wood composites are molded products that contain 90% to 30% inorganic binder. Accepted properties of inorganic bonded wood composites can be obtained only when the
wood particles are fully encased within the binder to make a coherent material.

Abdelgadir and Ibrahim (2003) concluded that compressive strength of wood-cement mixture is considerably reduced as cement / wood ratios are decreased for the five wood species they studied.

**2.6.2.4. Effect of treatment and additives**

Many investigators carried a series of tests to improve the compatibility of wood and cement by using some treatments (extraction or soaking of wood particles in some solutions such as hot water, calcium chloride and sodium hydroxide before its mixing with cement). On the other hand, some investigators carried out a series of tests designed to improve the wood-cement mixtures by addition of some chemicals such as calcium chloride and sodium hydroxide. The effect of treatments and additives on compatibility of wood-cement water mixtures are reviewed below:

Different methods were tried by researchers to treat wood in order to enhance its compatibility with cement. The logs are usually stored for at least three months to neutralize the sugars (TRADA 1985, Dinwoodie and Paxton 1983, and Anonymous 2001).

Iddi et al. (1997) studied the effect of unextracted chips of *Pinus patula* versus cold water extracted chips of the same species. Mean compressive strength of cement wood samples made from cold water extracted chips were significantly higher than those made from unextracted chips.

Gnanaharan and Dhamodaran (1985) examined the effect of water extraction on the suitability of 13 tropical hardwoods for wood-wool cement-board manufacture. They found that extraction with cold water was sufficient to remove the inhibitory extractives from most of the species tested.

Moslemi et al. (1983) determined that hot water extraction of larch (*Larix occidentalis*) particles greatly improved its compatibility with cement.
Moslemi and Lim (1984) found that hot water extraction substantially improved the compatibility of twelve species with cement. The time to reach maximum hydration temperature was greatly reduced.

Huffaker (1962) studied the use of planer mill residues in wood-fiber concrete. Fir, larch and spruce wood shavings were soaked in water or in a solution of CaCl₂. He found that a water soluble component of fir and larch shavings seriously retarded the setting of light weight concrete. Leaching the shavings helps to overcome the setting problem. Abdelgadir and Ibrahim (2002) indicated that treatment of wood with cold water improved compatibility of wood with cement for all the species studied, except *E. microthica*. The addition of calcium chloride was associated with the highest compressive strength except for *C. Procera* at low ratios.

Ahn *et al.* (1985) studied the effect of hot water extraction and the addition of CaCl₂ on the properties of wood–cement composites. They found that hot water extraction was more effective in the increase of modulus of rupture (MOR) than the addition of CaCl₂ in pine and larch. They indicated that CaCl₂ speeds up the hydration of cement without reacting with the wood substance. Hassan (1999) studied the effect of different levels of CaCl₂ on the properties of *Acacia nilotica* wood and cement mixture. He found that when wood was extracted, increasing the level of calcium chloride was associated with increase in strength properties.

Nasser (1996) stated that substantial improvements in cement setting can be achieved by using hot water and 1% NaOH solution treatments for Eucalyptus and Casuarina. The addition of CaCl₂ (3% cement weight basis) for the four species studied, improved compatibility with cement and the species can be classified as highly suitable. Abdalla (1998) used different treatments for sunt wood (*Acacia nilotica*). He soaked the particles in cold water for two weeks, also soaked them in 1% sodium
hydroxide solution for 24 hours, and added softwood sawdust (*Cupressus lucitanica*). He also added some chemicals such as calcium chloride (3%) based on cement weight and addition of 15% lime chloride (based on cement weight). He concluded that soaking in 1% sodium hydroxide solution and 15% commercial lime powder gave the highest improvement in the strength of the wood–cement boards. Moursi (2002) found that treating cotton stalks with hot water or NaOH (1%) had significant effect on compatibility with Portland cement. The combination of hot water and CaCl₂ as an additive had the best results.

Schwarz and Simatupang (1980) investigated the suitability of beech particles with cement using some pretreatments (steam, cold water, 5% NaOH and sodium carbonate) and untreated wood particles. They indicated that aqueous extraction appears to be the best method for pretreatment of beech. They also indicated that 90% of soluble sugars can be removed by cold water and 70% of hemicelluloses by 5% NaOH extraction. Kavvouras (1987) evaluated the suitability of *Quercus conferta* wood for the manufacture of cement-bonded flake boards. He used hot water and NaOH for the removal of soluble carbohydrates or addition of accelerators. He found that mixing 40% pine without treatment or 30% pine with hot water extraction was suitable. He indicated that CaCl₂ (1%) or NH₄Cl (3%) could be used as accelerators.

Badejo (1989) studied the influence of pretreatment with hot water (50 °C and 75 °C) and additive concentrations of aluminum sulphate on the properties of cement-bonded particleboards of some hardwood species. He indicated that the use of hot water at the higher temperature (75 °C) led to production of stronger panels but with less moisture resistance. Incorporation of aluminum sulphate resulted in stronger and more dimensionally stable boards. Lee and Short (1989) determined the effect
of four pretreatment (water, calcium chloride, sodium silicate and sodium hydroxide) on the bending properties of cement-bonded hardwoods and southern pine excelsior boards. They concluded that except for white oak and red oak the calcium chloride and sodium silicate treatments improved the static bending properties of the excelsior boards. Ibrahim (1995) studied the suitability of five hardwood species grown in different Sudanese environments for cement bonded particleboard. The species under investigation were *Acacia nilotica*, *Balanites aegyptiaca*, *Calatoropis procera*, *Eucalyptus camaldulensis* and *Eucalyptus microtheca*. She reported that all of them gave positive results and ranked as suitable when 3% calcium chloride (based on cement weight) was added. Shukla *et al.* (1984) studied the suitability of some wood and non-wood lignocellulosic materials with cement and found that improvement of strength properties was observed when calcium chloride accelerator was used. Lee and Hog (1986) concluded that the addition of calcium chloride (3% based on cement weight) to the mixture greatly increases the maximum hydration temperature, compressive strength and reduces hydration time.

Tami *et al.* (1995) stated that when magnesium chloride was used as an accelerator to cement setting, the inhibitory effect of sucrose contained in beech wood was lessened. Hassan (2000) studied the effect of extraction and chemical additives on compressive strength and some physical properties of wood-cement mixtures using *Acacia nilotica*, *Acacia senegal*, *Acacia seyal* and *Eucalyptus microtheca*. The woody materials of the four species were obtained from different Sudanese habitats. She concluded that some chemicals such as CaCl₂, FeCl₃, MgCl₂, and CaCO₃ improved the strength of wood-cement mixtures while others (MgSO₄, CaSO₄, MgCO₃, NaSO₄, Fe₂(SO₄)₃ and Na₂CO₃) reduced its strength. She also stated that species, extraction and chemical additives have a
significant influence on the compressive strength. She also found that increasing the levels of the chemical additives, was associated with increase in compressive strength of the mixture. Ma et al. (1996) studied the influence of the quantity of sodium silicate (Na$_2$SiO$_3$) additive, temperature of hot platen, Pressing time, water /cement ratio, cement /wood ratio, type of cement, and particle size on MOR and MOE. The best conditions according to them were 10 % addition of Na$_2$SiO$_3$, 95 ºC platen temperature, 12 minutes pressing time and 2.6:1 cement /wood ratio.

Collepardi et al. (1968) studied the effect of CaCl$_2$ on the hydration of tricalcium silicate (3CaOSiO$_2$) at 25ºC. They found that in the hydration of pastes, the amount of tricalcium silicate hydrated was proportional to CaCl$_2$ content. They also indicated that the surface area of the hydrated fraction of tricalcium silicate decreased with time if CaCl$_2$ is absent.

Ahn and Moslemi (1980) examined the effects of two Portland cement inhibitors (D-glucose and sucrose) and one accelerator (Calcium chloride) on bond formation in wood cement composites. They found that specimens containing calcium chloride exhibited cone-shaped well formed crystals in cement. That was believed to facilitate good interlocking not only within cement but also with wood. The strength of such specimens was much higher than that of controls containing no calcium chloride.

Young and Moslemi (1984) investigated the inhibitory index and the effect of hot water extraction treatment and addition of accelerators (CaCl$_2$, MgCl$_2$ and Ca (OH)$_2$ ) on the index in hardening lignocellulosic mixtures. They found that *Populus alba*, *Larix leptolepis* and *Pinus rigida* became highly suitable when treated with hot water and calcium and magnesium chlorides as additives.
Schmidt et al. (1994) indicated that chromium acts as an effective compatibility enhancing agent between cement and wood. Ma et al. (1996) stated that the compatibility of bamboo was improved by fermentation treatments.

2.6.2.5. The Effect of Water Used In the Mixture

Weatherwax (1964), Tarkow (1967) suggested that the amount of water needed for the mixture of cement and wood is about 0.25 ml per gram of cement and 2.7 ml per gram of wood (oven dry). Simatupang (1979) stated that the optimum amount of water for wood – cement mixture is inversely proportional to the specific weight of wood. Kumar et al. (1984) conducted two sets of experiments to study the suitability of lignocellulosic materials for the manufacture of cement bonded wood-wool boards. The ratio of cement wood flour and water for making cylindrical bodied were 15 grams wood flour, 200 grams Portland cement and 90 ml of water (2.7ml /g of wood flour plus 0.25 ml / g of cement).

Moslemi and Pfister (1987) stated that the quantity of distilled water added was calculated using the relationship developed by Simatupang (1979), according to the following formula:

\[
\text{Water (liters)} = 0.35C + (0.30 - MC) W
\]

Where:

- \( C \) = cement weight (Kg).
- \( MC \) = wood moisture content (oven dry basis)
- \( W \) = oven–dry wood weight (Kg).

Oyagade (1988) found that an amount of water equivalent to 65 % mass of cement was the most adequate for developing an efficient inter particle bonding when cement / wood ratios were in the range of 1.55:1 to 3.10:1.
Oyagade (1990) mentioned that theoretically, dry cement requires an amount of water equivalent to 23 % of its own weight for hydration process. In order to obtain a uniform coating of the cement on wood particles and for the completion of the hydration process, an amount of water in excess of that assigned theoretically is essential. He suggested 25 % to be used instead.

In the manufacture of cement bonded particleboard a mixture of Portland cement, wood and water is made in the ratio 3:1:1 of the respective components (Anonnomus 2001).

2.7. Effect of Processing Parameters on the Properties
Of Resin-Bonded Particleboard

The influences of raw material, compaction ratio, flake geometry, adhesive type and levels as well as pressing conditions were studied extensively during the last few decades. The results of previous work are reviewed below:

2.7.1. Effect of density and compaction ratio

The ratio between board density and wood density is defined as the compaction ratio. The two most important factors that affect the final properties of particleboard are the raw material density and the compaction ratio of the mat in the press. Any change of one of these factors requires an adjustment of the other if the average board density is to remain constant. Likewise, either of these factors can be changed to increase or decrease the average board density. Previous studies revealed that lower density species usually had higher strength properties than high density species (Hse et al. 1975, Price and Lehmann 1979).

Many researchers indicated that for conventional particleboard a density lower than the density of wood furnish will be unsatisfactory (Larmore 1959, Lynam 1959, Suchsland 1967, and Hse 1975). However, the compaction of the mat to an average density higher than the density of the
material furnish will allow better surface contact between the component particles of the mat. This results in a good adhesive utilization because more adhesive coated particles will be in intimate contact with other particles instead of with voids (Burrows, 1961 Hann et al. 1962, Lehmann, 1970, Shuler, 1974, and Hse 1975). Stegmann and Durst (1965) indicated that as the furnish density increases, the modulus of rupture (MOR) decreases at constant particleboard densities. Lehmann, (1970) reported that modulus of elasticity (MOE) was significantly affected by board density. Stewart and Lehmann (1973) concluded that MOR and MOE increased linearly with increasing panel density for four hardwood species ranging in specific gravity from 0.37 to 0.67 (OD weight, volume at 8 % m.c.). Internal bond (IB) strength was primarily related to panel density. Hse (1975) indicated that MOR, MOE and IB increased with increasing compaction ratios at all compaction ratios used (from 0.9 to 1.5). To produce satisfactory contact between particles it is necessary to compress the boards to a density of 1.2 to 1.6 times the wood density (Haygreen and Bowyer 1982). EL– Osta et al. 1988) showed that particleboard produced from casuarina wood had adequate strength, but was found to be lower in strength properties than flax boards. They attributed this result to the lower density of flax shives as compared to casuarinas wood as a raw material. The effect of raw material and compaction ratio on thickness swelling and water absorption were studied by many investigators. Some of these studies reported that thickness swelling (TS) increased with increasing board density. Others found minor or no change in TS with increasing particleboard density (Geimer 1982, Kuklewski et al. 1983, EL-Osta et al. 1988, Au and Gertjejunsen.1989).
Kelly (1977) reported that, no apparent consistent and reducible relationship between particleboard density and linear expansion (LE). No investigators had found a statistically valid relationship between LE and board density. He also indicated that linear expansion was much more dependent upon particle geometry and alignment.

Vital et al. (1980) reported that board density combined with resin content and flake geometry were the most important variable affecting (LE).

2.7.2. Modification of board properties by mixing raw materials

Several efforts were made in the past to blend different types of raw materials for particleboard manufacture. This was done to improve the quality of particleboard and to make use of the wood residues and the waste of some agricultural crops.

Vital et al. (1974) found that MOR and MOE of mixed species were equal to the weighed mean of the properties of boards made of one species at the same board density. Internal bond (IB) strength increased as the species density, from which the board is made, increased but also was affected to some extent by inherent characteristics of each species.

Coleman and Biblis (1976a) studied the properties of particleboard made from a mixture of particles of southern yellow pine and cottonwood. Their results indicated that, boards containing all cottonwood were 37% stiffer (MOE) and 70% stronger (MOR) in flexure than boards containing all pine furnish.

Thickness swelling (TS) was 29% higher for cottonwood boards. All pine wood particleboards were 54% higher in linear expansion than those containing all cottonwood. They attributed the results obtained to two factors, First, flake size distribution; cottonwood furnish contained a higher percentage of large flakes, while the amount of fines were appreciably higher in the pine furnish. Second, since the original density
of cottonwood was lower than that of pine and all boards were manufactured to the same density, boards with more cottonwood had a higher compaction ratio which resulted in a positive effect on the properties of particleboard.

Coleman and Biblis (1976b) also studied the properties of particleboard from various mixtures of sapwood and heartwood furnish of sweet gum. They found no appreciable differences in the flexural properties (MOR and MOE). Internal bond strength for boards containing all sapwood was 65% higher than that for boards containing all heartwood. They concluded that increasing the percentage of heartwood had a significant unfavorable effect on internal bond strength.

Price and Hse (1983) studied the properties of boards made with individual species and five different species combinations consisting of high density species (red oak 31%, ash 38%, overcup oak 11% and pecan 20%), low density species (sweet gum, hackberry and elm) and two combinations with two species mixture (hackberry 55% and pecan 45%, hackberry 55% and overcup oak 45%). Their results show that, with a seven species mixture, bending properties were higher than the three species mixture (sweet gum 55% red oak 20% and ash 25%) of low density and five species mixture of high density. However, panels made with the low density species, elm had lower bending properties than the two high density species, red oak and ash. They attributed this result to the anatomical characteristics, elm and hackberry, sometimes had interlocking grain that could result in a flake with low tensile strength. They also reported that the relationship between internal bond strength and panel types composed of more than one species generally paralleled the bending property relationship.

Planning and Gertjejansen (1985) in their study to evaluate the feasibility of using mixtures of balsam poplar and paper birch was not good to be
used with balsam poplar when mixed in equal proportions. However, 15% balsam poplar resulted in acceptable panels. On the other hand, using 50% paper birch with 50% balsam poplar required higher panel densities to achieve properties similar to panels from 100% aspen or balsam poplar.

Wojcik et al. (1989) indicated that a mixed species board with aspen in the face layer and red maple in the core layer had some of the highest static bending values. Dimensional stability values were also acceptable but some mixed species produced the lowest values. Subiyanto and Kawai (1996) concluded that thermosetting cement bonded particleboard prepared from albizia (*Pareserienthes falcatoria* (L) Nicolson) and mixtures of hinoki (*Chamaecyparis obtuse* Entl.) and sugi (*Cryptomeria japonica* D.Don) wood particles can be produced with very short pressing time. The optimum steam injection pressure with seal system was 2.5 Kgf/cm² showed the best physical and mechanical properties of the low density cement boards prepared from mixtures of sugi and hinoki.

### 2.7.3. Effect of particle configuration


Geimer and Crist (1980) examined the effect of chipping method on the properties of structural flake boards from short rotation intensively cultivated hybrid poplar clones. They indicated that the helical head chipper was ideally suited to chipping small diameter trees.

Au and Gertjejansen (1989) indicated that thicker wafers resulted in lower MORs and MOEs in both the non-aged and aged test conditions. IB strength increased with an increase in wafer thickness at low and medium
densities. However, IB strength was significantly higher at 3 % resin content for the thin wafers at all density levels. They also concluded that TS increased with an increase in wafer thickness (from 0.018 to 0.03 inches), but this was most noticeable in conjunction with a higher resin content. They also stated that thin wafers (0.018 inch) reduced LE than that obtained with thicker ones (0.027 and 0.036 inches).

2.7.4. Effect of resin content

It has been indicated that resin content is an important factor in improving the strength properties and dimensional stability of particleboards. Post (1958) concluded that particle geometry was much more significant than adhesive content with urea formaldehyde (UF) adhesive on MOR values.

Kimoto et al. (1964) used UF adhesives with different levels; 8, 10 and 15 % and found that only a slight improvement in strength properties with 15 % as compared to 10 % adhesive content.

Lehmann (1970) used UF at 2, 4 and 8 % resin contents and found only a small increase in MOR and MOE when adhesive content increased from 4% to 8%, but IB strength continued to increase substantially in this region.

Shuler (1974) used seven levels of UF resin ranging from 2 to 12 %. No improvement was evident to him in MOR and MOE when the adhesive level was increased above 5%. The 12 % adhesive content was below the 10 % level at all particleboard densities.

Lehmann (1978) indicated that the increases in strength properties were directly related to resin content.
Price and Lehmann (1979) also reported that increasing resin content from 5 to 8 % raised the MOR to an average of 16 % after accelerated ageing. The MOE trends were similar to those of bending strength (MOR).

Geimer and Crist (1980) reported that properties increased with an increase in resin content and decreased with a decrease in resin content with the use of either PF or UF resins.

Krzysik and Young (1986) using lignin–based adhesives, found that the maximum strength was achieved at about 10 % lignin–resin solids based on oven dry weight of wood flakes.

Generella et al. (1989) studied the mechanical properties of oriented flake boards. They reported that increasing the phenolic resin content from 4.5 to 6.5 % increased the mechanical properties.

Hann et al. (1963) indicated that particleboard durability was improved when the adhesive levels were increased from 3 % to 6 % and from 4 to 8 % for PF and UF adhesives, respectively.

Shuler (1974) used seven levels of UF adhesive ranging from 2 to 12 %, and concluded that Thickness swelling (TS) after both 2– and 24-hours' water soak tests attained a minimum at 10 % resin content and thereafter, no improvement in TS took place.

Lehmann (1978), Geimer and Crist (1980) observed that dimensional stability properties were improved by increasing resin content.

Krzysik and Young (1986) found that 10 % resin content gave the lowest values of TS after soaking for 2 – and 24-hours.

Generella et al. (1989) observed significant effect on TS when resin levels were increased but linear expansion (LE) was not significantly different when the resin content was raised from 4.5 to 6.5 %.

2.7.5. Effect of pressing time and temperature
Pressing time and temperature are extremely important parameters in particleboard manufacture. They have to be carefully controlled to insure that the core temperature is sufficient to cure the adhesive without subjecting the board surface to temperature degradation.

Lynam (1959) concluded that longer press cycles at lower temperatures, were better than short cycles at higher temperatures.

Kehr and Schoelzel (1965) studied the effect of platen temperature on compression time for three layers particleboard. They found that increasing the platen temperature from 120 to 180 °C, rapidly reduced the press time required for a mat moisture content of 11%.

Liiri (1969) also reported a decrease in the maximum pressure required to compact the mat as the press temperature increased. This is the result of increased plasticity of the wood as the temperature increased.

Heebink et al. (1972) indicated that satisfactory UF bonded particleboards could be manufactured when the center temperature was above 220 °F for 0.5 to 0.7 minutes.

John (1982) studied the effect of interactions of varying moisture contents, press temperature, and post-cure on MOR and MOE and IB of isocyanate bonded flake boards. Moisture contents used were 4, 8, 10 and 18 %. Press temperatures were 300, 350 and 400 °F. All boards were pressed to constant density profile by varying the press closing rates. He concluded that isocyanate bonded aspen flake boards can be made at press temperatures as low as 300 °F. Differences between under cured and adequately cured boards can result from as little as 15 seconds difference in press time and appear to be a function of both moisture content and press temperature.

2.7.6. Effect of press closing rate
The closure time is the time from press starts to reach a maximum required pressure. Quickly closing the press will subject the mat surfaces to platen heat and allow compressive failure at the mat surface before the interior has warmed sufficiently to permit the distribution of the compressive failure to a greater portion of mat thickness. Rice (1960) reported improved MOR and MOE values with an increased closing rate. Rice et al. (1967) reported that rapid press closure increased MOR and TS for uncatalyzed adhesives, but only slightly increased TS for the catalyzed resins. The internal bond (IB) for both the catalyzed and uncatalyzed adhesives flake boards dropped approximately 50% when the closing time of the press was increased from 1.5 to 3.4 minutes. Liiri (1969) reported that the maximum pressure required for mat consolidation decreased with increased closing time. The longer the mat was exposed to elevated temperature, the higher was the degree of wood plasticization and the lower the pressure required to compact it to the desired thickness. Heebink et al. (1972) found direct relationship between IB strength and press closure time. As the closing time increased, the core density increased and the IB increased. Geimer et al. (1975) reported that a fast closure time (20 seconds) resulted in a continuously decreasing density from the surface to the core. One minute closure time produced a maximum density approximately 1/16 inch below the surface while 3- minutes closure time resulted in vertical density gradient with a board peak from approximately 0.1 to 0.2 inch below surface. Kelly (1977) stated that the press closure rate influenced the properties related to vertical density gradient.

2.7.7. Effect of mat moisture content
The mat moisture content is an extremely critical factor. Stricker (1959) showed that the time required for heating the mat core decreased with increasing surface moisture content. Rice (1960) used mat moisture contents of 9, 12, and 15 % to study its effect on board properties. The MOR and MOE values were increased by 18 and 13 % respectively by increasing the mat moisture content from 9 to 15 %. Likewise the dimensional stability of the panels improved substantially, thereafter the board properties decreased by increasing mat moisture content.

Gatchell et al. (1966) reported an optimum static bending strength and internal bond (IB) strength at a moisture content of 12 %.

Heebink (1972) reported that 10 to 12 % to be the optimum moisture content for mats with uniform distribution. Lower moisture contents required higher pressers to consolidate the mat were characterized by poor inter-particle bonding. Higher moisture contents necessitated longer press cycles to allow sufficient moisture to escape.

John (1982) concluded that the most important process variable was mat moisture content. In all cases the 18 % moisture contents were weaker than either the 4 % or 10 % moisture content boards. However, the difference between the 4 % and 10 % boards was not significantly different.
Chapter 3
Materials and Methods

3.1. Materials used

Three lignocellulosic materials and two binders were used in this study as raw materials. The lignocellulosic materials were bagasse, cotton stalks and *Acacia nilotica* (sunt) sawdust. The binders were cement and urea formaldehyde.

### 3.1.1. Bagasse

Bagasse is a cellulose containing residue. It is a by-product of the sugar industry after the extraction of sugar from the cane. The material for this study is collected from EL Gunied sugar factory (Sudan).

### 3.1.2. Cotton stalks

Cotton (*Gossypium* spp.), is one of the oldest cultivated plants. It belongs to the family malvaceae. The species of cotton has many varieties. It grows up to 2 meters in height with a vertical branched stem, herbaceous to shrub-like shape. All cotton residues must be uprooted and burned. The stalks are collected into heaps and then set alight. The material under investigation was collected from Northern Gezera, Kamlin state, Sudan.

### 3.1.3. *Acacia nilotica* (sunt) sawdust

*Acacia nilotica* is a widely spread species in the northern part of tropical Africa. It grows on heavy black or dark grey alkaline clay in riverain basins or in areas that are periodically inundated. In the Sudan there are many small forests of *Acacia nilotica* along the Nile in the Blue Nile and Senar states. These forests are managed for the production of railway sleepers. Sunt is a hard and heavy timber, with specific gravity of about 0.8 at 12 percent moisture content. The material used in this study is the saw dust of *Acacia nilotica* wood collected from EL Suki sawmills (Sudan).

### 3.1.4. Cement
The type of cement used in this research was commercial Portland cement (type 1), meeting ASTM specifications C-150 and made by AL-Amriya Cement Company, Alexandria -Egypt.

3.1.5. Urea formaldehyde (UF)

The type of urea formaldehyde adhesive used in this research is produced by Ratinj King Company, Alexandria- Egypt. It is usually supplied with a separate hardener.

3.2. Preparation of the Lignocellulosic Raw Materials

Bagasse was processed by a hammermill, cotton stalks were processed first in a chipper then hammermilled. Then the three lignocellulosic materials (bagasse, cotton stalks and sunt sawdust) were screened using laboratory sieves to remove the oversize, fines and other impurities. The smaller particles which passed a sieve hole size of 0.8 mm and were retained on a sieve hole size of 0.4 mm (-20 +40 mesh) were used for hydration studies. The particles which passed a sieve hole size of 4 mm and were retained on a sieve size of 1 mm (- 4 +16 mesh), were used for particleboard manufacture (Figure 3.1).

3.3. Experiment 1: Effect of Treatments on Hydration Characteristics of Wood-Cement Mixtures

Preliminary hydration characterization was carried out for each of the three lignocellulosic materials to test its compatibility with ordinary Portland cement. The following treatments were used:

Treatment 1 (TRT 1) = control (untreated material) + cement.

Treatment 2 (TRT 2) = control + 3 % CaCl₂ (based on cement weight).

Treatment 3 (TRT 3) = Hot water (HW).

Treatment 4 (TRT 4) = HW + 3 % CaCl₂.

Treatment 5 (TRT 5) = 1 % NaOH.

Treatment 6 (TRT 6) = 1 % NaOH +3 % CaCl₂.
3.3.1. Treatments

3.3.1.1. Hot water treatment

An amount of 500 grams of wood meal, which passed through a 20 mesh screen and retained on a 40 mesh screen from each lignocellulosic material, was extracted in boiling water for six hours with changing the water every two hours time. The material was then washed twice with hot water. The particles were collected by pouring on a 200-mesh screen (0.08 mm), then washed with hot water and dried for 24 hours in an oven at 105±5°C.

Figure 3.1. The particle sizes of the three lignocellulosic materials used for board manufacture. (a) Bagasse, (b) Cotton stalk and (c) sunt sawdust
3.3.1.2. Sodium hydroxide treatment
An amount of 500 grams from each lignocellulosic material (-20 +40mesh) were soaked in a one percent solution of sodium hydroxide for 24 hours as described in ASTM-D1109-84, (1989). The material was then washed and dried as with the hot water treatment.

3.3.1.3. Chemical additive
An amount of 3 % calcium chloride (based on cement weight), was dissolved in water and added to the treated and untreated lignocellulosic materials as mentioned above.

3.3.1.4. Procedure of Hydration Test
An amount of 200 grams of ordinary Portland cement and 15 grams of oven dry lignocellulosic material from each species (-20 +40) mesh were dry mixed in a small plastic bag with or without the addition of calcium chloride for the treated and untreated materials. The mixture was then kneaded with 90.5 ml. of water for approximately 2 minutes. The plastic bag was wrapped with aluminum foil and then put in a Dewar flask. One end of the probes of a type K Thermocouple (Digi-Sense digital thermometer), was put inside the kneaded mixture of cement and wood and the other connected to the thermocouple. The plastic bag was then covered with fiber glass and the cap of the Dewar flask closed tightly. Figure 3.2 shows schematic representation of longitudinal section of the Dewar flask used.

The exothermic temperature was then recorded at suitable intervals. Finally the maximum temperature ($T_{\text{max.}}$) of the hydration reaction, and the time to reach that maximum ($t_{\text{max.}}$) were recorded.
Figure 3.2. A Schematic representation of a longitudinal section of the Dewar flask (H), (A) adhesive tape, (B) plastic sheet, (C) fiberglass, (D) thermocouple wire (E) aluminum foil, (F) polythene bag and (G) wood-cement water mixtures.
3.3.1.5. Statistical Analysis
Analysis of variance (ANOVA) and Duncan’s Multiple Range Test were conducted to study the significance of the difference between treatments using Statistical Analysis System (SAS) institute Inc. (1990).

3.4. Experiment 2: Wood chemical analysis
3.4.1. Determination of extractive contents
The extractive contents of the three lignocellulosic materials were determined according to ASTM Designation: D 1105-84 (1989).
The specimens were reduced by a Wiley mill so as to pass through a 60 mesh sieve and retained on 80 mesh sieve.
The specimens were extracted in the soxhlet apparatus with ethanol – benzene mixture in the ratio of one volume ethyl alcohol (95%) and two volumes chemically pure benzene for four hours, followed by extraction with 95% ethanol for four hours, then extraction with hot distilled water for three hours with changing water every one hour. The extracted specimens were then dried to a constant weight at 103 ± 2 °C and the extractive content was calculated as follows:
Extractive content % = \{(W_1 - W_2) / W_1\}*100
Where:
W_1 = Oven dry wood meal weight (g).
W_2 = extractive –free oven dry weight of wood meal (g).
The results were averaged from three replications.
3.4.2. Determination of lignin content
Lignin was determined according to the method described in the ASTM, D 1106-84 (1989).
The test specimens consisted of one gram of particles ground to pass a number 40 sieve size and thoroughly air dried.
The test specimens were first extracted with alcohol benzene mixtures. Then the specimens were hydrolyzed with a mixture of 89 % phosphoric acid and 75 % sulfuric acid (using the ratio of 1:6) at 35°C. After one hour, taken from the time of the addition of the acids, the specimens were secondarily hydrolyzed for half an hour by diluting with 200 ml of distilled water and boiling. The material was filtered while still hot through a previously dried and weighed Whatman filter paper No. 44. The lignin contained in the filter paper was washed with 50 ml distilled water to which some salt solution (Na Cl 0.5 g/liter) was added as an electrolyte. The filter paper with its content was dried at 103 ± 2 °C to a constant weight and weighed. Lignin content was calculated as a percentage based on the extractive-free oven dry weight of lignocellulosic particles.

3.4.3. Hot water solubility

Hot water solubility of the lignocellulosic materials under investigation was determined according to the method described in ASTM, D 1110-84 (1989). The test specimens were two grams air dried particles ground to pass a 40 mesh.

The two gram test specimen was placed in an erlenmeyer flask with 100 ml distilled water after its moisture content was determined. The flask was placed in a boiling water bath for three hours. The contents of the flask were then filtered on a glass fritted crucible using suction. The contents were then washed with hot water, dried to a constant weight at 100 to 105°C and finally cooled in a desiccator and weighed. The pH of extracts was measured using a pH meter. Hot water solubility was calculated using the following equation:

\[ \text{HWS} \% = \left( \frac{W_1 - W_2}{W_1} \right) \times 100 \]
Where:
\[ W_1 = \text{Weight of moisture–free specimen.} \]
\[ W_2 = \text{Weight of dried specimen after extraction.} \]
The results were averaged from three determinations.

3.4.4. Sodium hydroxide solubility

The solubility of the three lignocellulosic materials in 1 % sodium hydroxide was determined according to ASTM designation 1109-84 (1989).

Each specimen assigned for sodium hydroxide solubility determination was about two grams of an air dried particles that have been ground to pass a 40 mesh and retained on a 60 mesh. The test specimens were placed in a 200 ml, tall–form beakers and to each 100 ml of one percent sodium hydroxide solution was added. The covered beakers were placed in a steady boiling water bath (97 to 100 °C) and left in the bath for exactly one hour.

The extracted specimens were then filtered by suction on tared crucibles. The filtered meal was washed with 100 ml of hot water, then with 50 ml of acetic acid (10%) and again thoroughly with hot water. The crucibles and content were dried to a constant weight at 103±2 °C, cooled and weighed. The pH of extracts was measured using a pH meter.

Sodium hydroxide solubility (SHS) was calculated as follows:

\[ \text{SHS \%} = \left( \frac{W_1 - W_2}{W_1} \right) \times 100 \]

Where:
\[ \text{SHS\%} = \text{Matter soluble in caustic soda} \%
\]
\[ W_1 = \text{Weight of moisture free wood in specimens prior to test.} \]
\[ W_2 = \text{Weight of dried specimen after treatment with NaOH solution.} \]
The results were averaged from three replications.
3.4.5. Statistical Analysis
Analysis of variance (ANOVA) and Duncan’s Multiple Range Test were conducted to study the significance of the differences between treatments using Statistical Analysis System (SAS) institute Inc. (1990).

3.5. Experiment 3: Effect of Mixing the Three Lignocellulosic Materials on the Properties of Cement-Bonded Particleboard
3.5.1. Manufacturing process
The preliminary hydration tests revealed that, the best common effective treatment for the compatibility of all the lignocellulosic materials under investigation with cement, was (TRT 6) which was using 1% NaOH solution (24 hours soaking) and 3 % CaCl₂ as an additive or accelerator for cement setting. The maximum hydration temperatures reached were above 60ºC. Hence this treatment was chosen for the furnish treatment of cement bonded particleboards.

3.5.1.1. Board specifications
Dimensions: 30 x 30 x 1 cm.
Density: 1.2 (g/cm³)
Ratios of cement to wood: 2.5:1, 3:1, 3.5:1 and 4:1.
Pressures used: 25, 20, 15 and 10 metric tons equivalent to 27.8, 22.2, 16.7 and 11.1 (Kg/cm²), for the above mentioned ratios respectively.
The amount of water used for furnish mixing was calculated according to the relationship developed by Simatupang (1979).
Nine mixtures were made from the three lignocellulosic materials. The different mixtures and amounts of materials are as shown in Tables 3.1 and 3.2.
Table 3.1 Different mixtures of the three lignocellulosic materials

<table>
<thead>
<tr>
<th>Board type</th>
<th>Bagasse %</th>
<th>Cotton stalks %</th>
<th>Sunt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>M2</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>M3</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>M4</td>
<td>50</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>M5</td>
<td>50</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>M6</td>
<td>0</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>M7</td>
<td>25</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>M8</td>
<td>25</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>M9</td>
<td>50</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 3.2 Cement Wood Ratios (C/W) and amounts of materials used.

<table>
<thead>
<tr>
<th>C/W Ratio</th>
<th>Cement (g)</th>
<th>100% wood</th>
<th>50% wood</th>
<th>25% wood</th>
<th>CaCl₂ (g)</th>
<th>Water (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5:1</td>
<td>771.4</td>
<td>308.57</td>
<td>154.3</td>
<td>77</td>
<td>23.13</td>
<td>328.42</td>
</tr>
<tr>
<td>3:1</td>
<td>810</td>
<td>270</td>
<td>150</td>
<td>67.5</td>
<td>24.3</td>
<td>334.8</td>
</tr>
<tr>
<td>3.5:1</td>
<td>840</td>
<td>240</td>
<td>120</td>
<td>66.6</td>
<td>25.2</td>
<td>339.6</td>
</tr>
<tr>
<td>4:1</td>
<td>864</td>
<td>216</td>
<td>108</td>
<td>60</td>
<td>25.9</td>
<td>344</td>
</tr>
</tbody>
</table>
3.5.1.2. Mixing of board components
The lignocellulosic particles were weighed and mixed with the determined amounts of dry cement (Portland cement type 1 meeting ASTM specifications C-150). Then the right amount of CaCl₂ for each mixture was dissolved in the predetermined amount of water. The solution was added to the blend of cement and wood and thoroughly hand mixed in plastic containers for about 5 minutes.

3.4.1.3. Mat formation
Open top boxes consisting of a frame from beech wood, a base and cover of veneer plywood coated with phenolic films, were made. The bases were fixed and released from the frames by means of nails and screw drivers. The boxes were designed to give 30 x 30 cm for the base from inside and a frame height of 3.2 cm. and a cover with a thickness of 2.2 cm to fit tightly in the frame and to give a thickness of one centimeter for the intended boards (Figure 3.3).

The mixture of cement, water, and lignocellulosic materials with the additive were formed in each box, by hand (Figure 3.4). Then the square covers of the layered veneer plywood were placed on the top of the mixture to press it and ensure the desired thickness of boards. Three replicates were made from each of the nine mixtures of the four ratios

3.5.1.4. Pressing of the boards
The manufactured boards were pressed in a cool hydraulic press (Carver, model 2699) under constant pressure (Figure 3.5). The amount of pressures used were, 27.7 Kg/cm², 22.2 Kg/cm², 16.67 Kg/cm² and 11.11Kg/cm² depending on the cement wood ratios used. The boards were pressed for few minutes until the required pressure is reached. Then the boxes containing the boards were removed and clamped overnight in a locally made manual clamp (Figure 3.6).
Figure 3.3. Open top boxes used for mat formation. (a) Base (b) frame (c) cover.
Figure 3.4. Hand felted wood-cement furnish formed in the mould.
Figure 3.5. The Carver Hydraulic press (model 2699), used for pressing the moulds.
Figure 3.6. The locally made clamp used for clamping the wood-cement boards in the moulds
3.5.1.5. Conditioning
Following the 24 hours setting period, the boards were carefully released from the moulds, misted with water and wrapped in cellophane to enhance hydration Figure (3.7). The boards were then racked vertically at ambient room temperature and left to cure for 28 days (Figure 3.8).

3.5.2. Determination of properties

3.5.2.1. Experimental design
Representative samples of cement bonded particleboard were randomly chosen from the manufactured boards. The specimens were chosen for testing their properties using the completely randomized design (CRD).

3.5.2.2. Physical properties

3.5.2.2.1. Density
Representative square pieces with sides of nominal length of 50 mm were prepared from each replicate of boards according to DIN EN 323. The dimensions of each test piece were measured to an accuracy of 0.05 mm. Each specimen was weighed to an accuracy of 0.01 g. Then the density of the samples was calculated as the following:

\[ \text{Density} = \frac{\text{sample mass}}{\text{sample volume}}. \]

3.5.2.2.2. Moisture content
Square pieces 5 x 5 cm were prepared according to ASTM 1037. The samples were weighed to the nearest 0.1 gram, dried in an oven at 103±2 °C until weight consistency and their dry weights recorded. The moisture content of the samples was then determined as follows:

\[ \text{Moisture content (\%)} = \left\{ \frac{W_1 - W_2}{W_2} \right\} \times 100 \]
Figure 3.7. Wrapping of boards in cellophane.
Figure 3.8. Curing of boards in a conditioning room
3.5.2.2.3. Water absorption

The test pieces were squares with a side length of (50±1) mm. The primary weights of the samples were determined to the nearest 0.1 gram. The dimensions of the samples were measured to the nearest 0.05mm using a caliper at chosen points. The test pieces were immersed with their faces vertical, in a water bath at room temperature for two hours, then were taken out, dried with cotton cloth, weighed, and their dimensions measured again at the same previously determined points. The samples were then soaked again for 24 hours, taken out, dried, weighed and their dimensions measured as described before. Water absorption percent was calculated as follows:

WA₂ = \{(W₂-W₁)/W₁\}×100

Where:

WA₂ = water absorption percent after two hours.
W₂ = sample weight after two hours soaking.
W₁ = sample weight before soaking.

WA₂₄ = \{(W₂₄-W₁)/W₁\}×100

Where:

WA₂₄ = water absorption percent after 24 hours.
W₂₄ = weight after 24 hours soaking.
W₁ = weight before soaking.
3.4.2.2.4. Thickness swelling

Swelling in thickness was determined by measuring the increase in thickness of the test piece after complete immersion in water. This test was carried out as specified by the European standard EN 313:1993. The test pieces were square in shape, with a side length of $\langle 50 \pm 1 \rangle$ mm.

The thickness of each test piece was measured to an accuracy of 0.01 mm at the intersection of the diagonals according to EN 324-1:1993. The specimens were immersed, with their faces vertical and separated from each other and from the bottoms and sides of a water bath. After two hours the test pieces were taken out of the water, excess water removed, and the thickness of each specimen was measured. Then the specimens were immersed again to complete 24 hours immersion time. The thickness was measured again after the 24 hours immersion period.

The results of thickness swelling were expressed as a percentage of the original thickness according to the following equation:

$$TS_2 = \{(t_2 - t_1)/t_1\} \times 100$$

Where:
- $TS_2 =$ Thickness swelling after two hours immersion.
- $t_2 =$ Thickness of the test piece after immersion for two hours.
- $t_1 =$ Thickness of the test piece before immersion in mm.

For the 24 hours time ($TS_{24}$), it is expressed as follows:

$$TS_{24} = \{(t_{24} - t_1)/t_1\} \times 100$$

Where:
- $TS_{24}$ = Thickness swelling after 24 hours immersion in mm.
- $t_{24}$ = Thickness of the test specimen after immersion for 24 hours in mm.
- $t_1 =$ Thickness of the test piece before immersion in mm.
3.5.2.3. Mechanical properties

3.5.2.3.1. Static bending test

The test specimens for static bending test were prepared and tested according to the American Standard for Testing and Materials (ASTM D-1037) with some modifications due to the limited size of boards. The dimensions of the specimens were 25 x 5 x 1 cm. The span was 23 cm. The test was carried out using Lloyd testing machine. Modulus of rupture (MOR) and modulus of elasticity (MOE) were calculated from the curves produced using the following equations:

\[ \text{MOR} = 1.5 \frac{P_l}{bh^2} \]

Where:
MOR = Modulus of rupture (Kg/Cm²)
P = Maximum load in Kgf
l = span in centimeters
b = width of the specimen in cm.
h = thickness of the specimen in cm.

\[ \text{MOE} = \frac{P_l l^3}{4bh^3D} \]

Where:
MOE = Modulus of elasticity
P_l = load at the limit of proportionality
l = span in centimeters
b = Width of the specimen in cm.
h = Thickness of the specimens in cm
D = deflection in cm

3.5.2.4. Statistical Analysis

Analysis of variance (ANOVA) and Duncan’s Multiple Range Test were conducted to study the significance of the differences between treatments using Statistical Analysis System (SAS) institute Inc. (1990).
3.6. Experiment 4: Effect of Mixing the Three Lignocellulosic Materials on the Properties of Resin-Bonded Particleboard

3.6.1. Manufacturing process

This experiment was carried out to study the effect of mixing different lignocellulosic materials on the properties of particleboard produced.

3.6.1.1. Manufacturing variables

Panel volume: 30 cm x 30 cm x 1.2 cm
Panel density: 700 Kg/m³.
Resin type: Urea formaldehyde (UF).
Resin solid content: 60%.
Hardener: Ammonium chloride (1% of solid resin).
Pressure used: 27 Kg/cm².
Pressure time: 12 seconds per millimeter of thickness.
Closure time: one minute.
Final mat moisture content: 13%.
Number of mixes: 10.
Panel type: Nine homogenous and one layered.
Ratios of the lignocellulosic materials: From mix 1 to mix 9 as shown on table (3.3). Mix. 10 ; core 50 % cotton stalks, face and back equal mixtures of bagasse (25%) and sunt sawdust (25%) blended carefully and then divided equally between the two faces.

3.6.1.2. Resin blending

To obtain a board with a target density of 700 Kg/cm³, 786.24 grams (oven dry weight) of the lignocellulosic material were mixed with 126 grams of urea formaldehyde resin using a laboratory type blender (Figure 3.9). The blender was designed and manufactured at the Faculty of Agriculture, Alexandria University. It consists of a motor with 1200 cycles per minute a gear box or reducer to obtain 300cycles per minute and a container with central stirring shaft. To reach the final moisture
content for the mattress, the required amount of water was calculated and added. The mixture was blended for about 6 minutes to ensure thorough resination of the particles.

3.6.1.3. Mat formation

Immediately after resin application and blending, the resinated particles were hand felted onto caul plates into a wooden forming frame. Thereafter the frame was removed and the mattress with its enclosed stainless steel caul plates (30 cm x 30 cm) were wrapped with aluminum foil and transferred to the hot press.

Figure 3.9. The locally made blender used for mixing the glue with the lignocellulosic particles.
3.6.1.4. Hot pressing

The mat was pressed at 150 °C pressing temperature for 2.5 minutes using Carver laboratory press, model 2699 (Figure 3.5). The pressure used was 27.8 Kg/cm².

3.6.1.5. Conditioning

The boards were then placed at 65±5% relative humidity (RH) and 20 °C to reach equilibrium moisture content.

Ten mixes of boards each replicated three times were manufactured.

3.6.2. Test specimens for evaluation of strength properties and dimensional stability

The specimens for the mechanical and physical properties of boards produced were prepared and tested according to ASTM D-1037 (1989). The specimens for bending strength were slightly modified due to small size of boards. Their dimensions were as described for the specimens used for determining the static bending for the cement bonded particleboard. The Internal bond (IB) specimens were 5 x 5 cm and had the same thickness of the boards. The samples were adhered with a hot melt adhesive from both their upper and lower faces with a couple of aluminum jaws. The jaws were manufactured to fit the accessories of the INSTRON-1195 testing machine parts assigned for internal bond test.

The dimensional stability tests i.e. Water absorption (WA) and thickness swelling (TS) were evaluated as described for cement bonded particleboard.
3.6.3. Statistical Analysis

Analysis of variance (ANOVA) and Duncan’s Multiple Range Test were conducted to study the significance of the differences between treatments using Statistical Analysis System (SAS) institute Inc. (1990).
Chapter Four

Results and Discussion

4.1. Effect of Treatments on Hydration Characteristics

Mean values for maximum hydration temperature ($T_{\text{max}}$), time to reach maximum temperature ($t_{\text{max}}$) and rise in temperature above the ambient ($\Delta T$) of wood cement mixtures of the three lignocellulosic materials are presented in Table 4.1. Values of maximum hydration temperature obtained for different materials in cement mixtures with and without calcium chloride ($\text{CaCl}_2$) accelerator are given in Table 4.2.

4.1.1. Maximum hydration temperature

It may be seen from Tables 4.1 and 4.2 that all the untreated lignocellulosic materials used depressed the temperature rise during the setting process. The extent to which suppression of temperature takes place is a measure of the retarding effect of the wood and non-wood lignocellulosic materials on cement setting. Wood with minimum suppression effect is more suitable and those causing greater temperature depression interfere with cement setting process and are likely to be less suitable for wood – cement board manufacture (Jain et al. 1989).

The three materials used in this study, when mixed with cement without any treatment, appreciably decreased the temperature rise when compared to neat cement (Figure 4.1), and hence they are all considered incompatible.
Table 4.1. Mean values for maximum hydration temperature ($T_{\text{max}}$), time to reach maximum hydration Temperature ($t_{\text{max}}$) and rise in temperature above the ambient ($\Delta T$) for the three lignocellulosic materials.

<table>
<thead>
<tr>
<th>Species</th>
<th>Treatment</th>
<th>Additive</th>
<th>$T_{\text{max}}$ (°C)</th>
<th>$t_{\text{max}}$ (hrs)</th>
<th>$\Delta T$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sunt</td>
<td>None</td>
<td>None</td>
<td>36.7</td>
<td>20.0</td>
<td>9.1</td>
</tr>
<tr>
<td>sunt</td>
<td>None</td>
<td>CaCl2</td>
<td>68.4</td>
<td>4.09</td>
<td>39.6</td>
</tr>
<tr>
<td>sunt</td>
<td>Hot water</td>
<td>None</td>
<td>48.5</td>
<td>11.6</td>
<td>20.0</td>
</tr>
<tr>
<td>sunt</td>
<td>Hot water</td>
<td>CaCl2</td>
<td>70.0</td>
<td>3.8</td>
<td>41.4</td>
</tr>
<tr>
<td>sunt</td>
<td>1%NaOH</td>
<td>None</td>
<td>55.3</td>
<td>10.0</td>
<td>26.7</td>
</tr>
<tr>
<td>sunt</td>
<td>1%NaOH</td>
<td>CaCl2</td>
<td>67.9</td>
<td>4.4</td>
<td>39.2</td>
</tr>
<tr>
<td>Cotton stalks</td>
<td>None</td>
<td>None</td>
<td>35.9</td>
<td>+24</td>
<td>11.1</td>
</tr>
<tr>
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<td>None</td>
<td>CaCl2</td>
<td>42.2</td>
<td>14</td>
<td>13.3</td>
</tr>
<tr>
<td>Cotton stalks</td>
<td>Hot water</td>
<td>None</td>
<td>47.3</td>
<td>11</td>
<td>18.9</td>
</tr>
<tr>
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<td>Hot water</td>
<td>CaCl2</td>
<td>67.3</td>
<td>4.4</td>
<td>38.6</td>
</tr>
<tr>
<td>Cotton stalks</td>
<td>NaOH</td>
<td>None</td>
<td>50.9</td>
<td>10.8</td>
<td>21.9</td>
</tr>
<tr>
<td>Cotton stalks</td>
<td>NaOH</td>
<td>CaCl2</td>
<td>67.9</td>
<td>4.8</td>
<td>39.2</td>
</tr>
<tr>
<td>Bagasse</td>
<td>None</td>
<td>None</td>
<td>35.5</td>
<td>+24</td>
<td>8.0</td>
</tr>
<tr>
<td>Bagasse</td>
<td>None</td>
<td>CaCl2</td>
<td>42.1</td>
<td>15</td>
<td>17.0</td>
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<tr>
<td>Bagasse</td>
<td>Hot water</td>
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<td>34.8</td>
<td>12</td>
<td>5.3</td>
</tr>
<tr>
<td>Bagasse</td>
<td>Hot water</td>
<td>CaCl2</td>
<td>52.3</td>
<td>5.5</td>
<td>23.9</td>
</tr>
<tr>
<td>Bagasse</td>
<td>NaOH</td>
<td>None</td>
<td>34.8</td>
<td>9.8</td>
<td>6.4</td>
</tr>
<tr>
<td>Bagasse</td>
<td>NaOH</td>
<td>CaCl2</td>
<td>63.9</td>
<td>4.4</td>
<td>35.4</td>
</tr>
</tbody>
</table>
Table 4.2. Effect of treatments with and without calcium chloride as accelerator on maximum hydration temperature for the three lignocellulosic materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Treatment</th>
<th>Without accelerator</th>
<th>With accelerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunt</td>
<td>None</td>
<td>36.7</td>
<td>68.4</td>
</tr>
<tr>
<td></td>
<td>Hot water</td>
<td>48.5</td>
<td>70.0</td>
</tr>
<tr>
<td></td>
<td>1% NaOH</td>
<td>55.3</td>
<td>67.9</td>
</tr>
<tr>
<td>Cotton Stalks</td>
<td>None</td>
<td>35.9</td>
<td>42.2</td>
</tr>
<tr>
<td></td>
<td>Hot water</td>
<td>47.3</td>
<td>67.3</td>
</tr>
<tr>
<td></td>
<td>1% NaOH</td>
<td>50.9</td>
<td>67.9</td>
</tr>
<tr>
<td>Bagasse</td>
<td>None</td>
<td>35.5</td>
<td>42.1</td>
</tr>
<tr>
<td></td>
<td>Hot water</td>
<td>34.8</td>
<td>52.3</td>
</tr>
<tr>
<td></td>
<td>1% NaOH</td>
<td>34.8</td>
<td>63.7</td>
</tr>
</tbody>
</table>
The addition of 3 % CaCl₂ (cement weight basis) to the mixture slightly improved the maximum hydration temperature for the untreated cotton stalks and bagasse particles by 17.6 % and 18.49 % respectively. Greater improvement 86.22 % have been seen when 3 % CaCl₂ (cement weight basis) was added to the untreated sunt sawdust. Thus sunt wood can be classified as suitable or compatible with cement when calcium chloride is used as accelerator.

Figures 4.2, 4.3 and 4.4 show the effect of different treatments on hydration characteristics of sunt, cotton stalks and bagasse, respectively. Treating the three lignocellulosic materials with hot water slightly improved the maximum hydration temperature for both sunt and cotton stalk-cement mixtures (48.5 and 47.3 %, respectively). The three lignocellulosic materials can still be considered incompatible since the maximum hydration temperature is below (60 °C). Addition of 3% calcium chloride as accelerator for the three materials when treated with hot water increased the hydration temperature by 44.5 % for sunt sawdust, 42.35 % for cotton stalks particles and 50.3% for bagasse particles. Sunt wood and cotton stalk particles can then be classified as compatible after extraction with hot water and addition of calcium chloride. Bagasse is still unsuitable for cement mixtures.
Figure 4.1. Exothermic curves of the untreated lignocellulosic materials–cement mixtures as compared to neat cement.

Figure 4.2. Exothermic curves of Sunt wood–cement mixtures under different treatments.
Legend:
TRT-1 = Untreated wood. TRT-2= TRT-1+3%CaCl₂. TRT-3 = Hot water. TRT-4=TRT-3+3%CaCl₂. TRT-5=1%NaOH. TRT-6=TRT-5+3%CaCl₂.
Figure 4.3. Exothermic curves of cotton stalks-cement mixture under different treatments.
Legend:
TRT-1=Untreated wood. TRT-2 =TRT-1+3%CaCl₂. TRT-3=Hot water. TRT-4=TRT-3+3% CaCl₂. TRT-5=1%NaOH. TRT-6=TRT-5+3%CaCl₂.

Figure 4.4. Exothermic curves of bagasse-cement mixtures under different treatments.
Legend:
TRT-1=Untreated wood. TRT-2 =TRT-1+3%CaCl₂. TRT-3=Hot water. TRT-4=TRT-3+3% CaCl₂. TRT-5=1%NaOH. TRT-6=TRT-5+3%CaCl₂.
When the three lignocellulosic materials were treated with 1% NaOH without additive, similar results to those obtained with hot water treatment without additive were also observed. Figures 4.5, 4.6 and 4.7 show the effect of hot water and 1% NaOH extraction methods without additive on hydration characteristics of the three lignocellulosic materials used. When 3 % calcium chloride was added to the weak alkali treated materials, the maximum hydration temperature of the three lignocellulosic materials under investigation exceeded 60 ºC and hence rendered suitable for cement mixing. The rise in maximum hydration temperature due to the addition of calcium chloride to the 1% NaOH treated materials was about 22.7 % for sunt wood, 33.4% for cotton stalks and 83.5% for bagasse particles. Figures 4.8, 4.9 and 4.10 show the effect of calcium chloride on the treated and untreated lignocellulosic materials used.

The analysis of variance for the different treatments with regard to the maximum hydration temperature (T_max) variable is highly significant (p = 0.0001). For the mean separation test and Duncan’s grouping, see Figure 4.11 and appendix (1).

4.1.2. Time to reach maximum hydration temperature:

The results presented in Table 4.1 and Figure 4.1 indicate that the untreated lignocellulosic materials-cement –water system completely failed to set over the 24-hour test period. Highly significant differences exist between the times taken to reach the maximum hydration temperature (t_max).

The effect of addition of calcium chloride on the admixture of cement-water-lignocellulosic materials is presented in Table 4.3. The assessment of these results indicated that the addition of 3 % CaCl_2 reduces the reaction of hydration time of the untreated sunt sawdust from 20 hours to
4.1 hours. Similar reduction in hydration time to reach maximum temperature was also recorded for the two other treatments. The time to reach maximum temperature for hot water treated sunt sawdust was reduced from 11.58 hours to 3.84 hours. For the weak alkali (1% NaOH) treated sunt sawdust a reduction in time to reach maximum temperature from 10.0 hours to 4.4 hours was recorded.

The analysis of variance for the time to reach maximum hydration temperature ($t_{\text{max}}$) for sunt sawdust-cement showed highly significant variations between all the treatments used ($p = 0.0001$). The analysis of variance and the Duncan's grouping are shown in Figure 4.12 and appendix (2).
Figure 4.5. Effect of hot water and 1% NaOH extraction without chemical additives on hydration characteristics of sunt wood–cement mixtures compared to untreated sunt wood -cement mixtures.

Legend:
TRT-1= Untreated wood. TRT-2 = TRT-1+ 3 % CaCl₂. TRT- 3 = Hot water. TRT-4 = TRT-3 +3 % CaCl₂. TRT-5 = 1 %NaOH.

Figure 4.6. Effect of hot water and 1% NaOH extraction without chemical additives on hydration characteristics of cotton stalks wood –cement mixtures compared to untreated cotton stalks -cement mixtures.

Legend:
TRT-1 = Untreated wood. TRT-2 = TRT-1+3 % CaCl₂. TRT-3 = Hot water. TRT-4 = TRT-3 + 3 % CaCl₂. TRT-5 = 1 %NaOH.
Figure 4.7. Effect of hot water and 1%NaOH extraction without chemical additive on the hydration characteristics of bagasse compared to untreated bagasse .

Legend:
TRT-1 = Untreated wood. TRT-2 = TRT-1 + 3 % CaCl₂. TRT-3 = Hot water. TRT-4 = TRT-3 + 3 % CaCl₂. TRT-5 = 1 % NaOH.

Figure 4.8. Effect of calcium chloride on the hydration characteristics of treated and untreated sunt wood-cement mixtures.

Legend:
TRT-1 = Untreated wood. TRT-2 = TRT-1 + 3 % CaCl₂. TRT-3 = Hot water. TRT-4 = TRT-3 + 3 % CaCl₂. TRT-5 = 1 % NaOH. TRT-6 = TRT-5 + 3 % CaCl₂.
Figure 4.9. Effect of calcium chloride on the hydration characteristics of treated and untreated cotton stalks wood-cement mixtures.
Legend:
TRT-1 = Untreated wood. TRT-2 = TRT-1 + 3% CaCl2. TRT-3 = Hot water.
TRT-4 = TRT-3 + 3% CaCl2. TRT-5 = 1% NaOH. TRT-6 = TRT-5 + 3% CaCl2.

Figure 4.10. Effect of calcium chloride on the hydration characteristics of treated and untreated bagasse-cement mixtures.
Legend:
TRT-1 = Untreated wood. TRT-2 = TRT-1 + 3% CaCl2. TRT-3 = Hot water.
TRT-4 = TRT-3 + 3% CaCl2. TRT-5 = 1% NaOH. TRT-6 = TRT-5 + 3% CaCl2.
Figure 4.11. Maximum hydration temperature attained by different treatments of the three lignocellulosic materials.

*Bars with similar letters in each species are not significantly different according to Duncan's test.

Legend:
TRT-1 = Untreated wood. TRT-2 = TRT-1 + 3% CaCl₂. TRT-3 = Hot water. TRT-4 = TRT-3 + 3% CaCl₂. TRT-5 = 1% NaOH. TRT-6 = TRT-5 + 3% CaCl₂.

The maximum hydration temperature recorded for the untreated cotton stalks and bagasse-cement mixtures during the 24-hour test period was reached in a very short time. This temperature rise depicts the general pattern of hydration reactions of neat cement and wood-cement-water mixtures. For both bagasse and cotton stalks untreated particles, the temperature at the start of the reaction was about 35°C, then dropped a bit and flattened to about 29 to 30°C during the 24-hour preliminary test-period used. It was anticipated that the actual maximum hydration temperature for the untreated bagasse and cotton stalks to take a fairly longer time than the 24-hour test period conducted. When the 3% calcium chloride was added as an accelerator for the two untreated lignocellulosic materials-cement mixtures, the hydration temperature reached about 42°C for both of them again in a very short time (39-56
minutes) for the six replicates. The chemical additive does not appear to have neutralized the detrimental effect of high inhibitory species on exothermic reactions of cement. This statement is in agreement with Moslemi et al. (1983) but in contradiction with earlier conclusions made by Bibilis and Lo (1968). An other possible explanation is that the additive is believed to speed up the rate of hydration of plain cement without reacting with the wood substance (Moslemi et al. 1983).

The effect of CaCl₂ as an accelerator on the time to reach maximum temperature for both cotton stalks and bagasse was also significant for the different treatments (P= 0.0001). For the analysis of variance see appendix (2), and for Duncan's grouping see Figure 4.12.

Figure 4.12. Mean values of time to reach maximum hydration temperature (t_{max}) as an effect of treatments on the three lignocellulosic materials.
* Bars with similar letters for each species are not significantly different according to Duncan's test.

Legend:
TRT-1 = Untreated wood. TRT-2 = TRT-1+ 3 % CaCl₂. TRT-3 = Hot water. TRT-4 = TRT-3 + 3 % CaCl₂. TRT-5 = 1 % NaOH. TRT-6 = TRT-5 + 3 % CaCl₂.
4.1.3. Rise in temperature above the ambient (ΔT)

The results presented in Table 4.1 show the magnitude of the rise of temperature above the ambient for the different treatments used. The effect of different treatments on the rise in temperature above the ambient follows a similar pattern as the maximum hydration temperature. The lowest values were observed with the untreated materials and with the other two treatments when the 3 % CaCl2 was not added. The highest values in general are associated with hot water and 1 % NaOH when the calcium chloride is used as an accelerator. A remarkable rise in temperature above the ambient is recorded with the untreated sunt sawdust when the additive is used.

The analysis of variance for (ΔT) for the three lignocellulosic materials shows a highly significant differences among the treatments used (p=0.0001). It was clear from Figure 4.13 that the addition of CaCl2 appreciably affected the temperature rise above the ambient for all the lignocellulosic materials. For the Duncan's grouping see Figure 4.13 and for ANOVA see appendix (3).
Table 4.3. Effects of Calcium Chloride on the time to reach maximum hydration temperature

<table>
<thead>
<tr>
<th>Material</th>
<th>Treatment</th>
<th>Without additive</th>
<th>With additive</th>
</tr>
</thead>
<tbody>
<tr>
<td>sunt</td>
<td>Untreated</td>
<td>20</td>
<td>4.1</td>
</tr>
<tr>
<td>sunt</td>
<td>Hot water</td>
<td>11.6</td>
<td>3.8</td>
</tr>
<tr>
<td>sunt</td>
<td>1%NaOH</td>
<td>10.0</td>
<td>4.4</td>
</tr>
<tr>
<td>Cotton stalk</td>
<td>Untreated</td>
<td>+24</td>
<td>14</td>
</tr>
<tr>
<td>Cotton stalk</td>
<td>Hot water</td>
<td>11</td>
<td>4.4</td>
</tr>
<tr>
<td>Cotton stalk</td>
<td>1%NaOH</td>
<td>10.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Bagasse</td>
<td>Untreated</td>
<td>+24</td>
<td>+15</td>
</tr>
<tr>
<td>Bagasse</td>
<td>Hot water</td>
<td>12</td>
<td>5.5</td>
</tr>
<tr>
<td>Bagasse</td>
<td>1% NaOH</td>
<td>9.9</td>
<td>4.5</td>
</tr>
</tbody>
</table>
Figure 4.13. Mean values of rise in temperature above the ambient (ΔT) as an effect of treatments for the three lignocellulosic materials used.
* Bars with the same letters in each species are not significantly different according to Duncan's test.

Legend:
TRT-1 = Untreated wood. TRT-2 = TRT-1+ 3 % CaCl₂. TRT-3 = Hot water.
TRT-4 = TRT-3 + 3 % CaCl₂. TRT-5 = 1 % NaOH. TRT-6 = TRT-5 + 3 % CaCl₂.

4.2. Wood Chemical Analysis
4.2.1. Extractives Content

Average values of the results of the extractive contents determination of the three lignocellulosic materials are shown in Table 4.4. Extractives are materials soluble in neutral solvents. These materials should be removed before any chemical analysis of wood. Ethanol-benzene extracts waxes, fats, some resins and portions of wood gums as well as some water soluble substances. Non-polar extractives may migrate to the wood surface during drying and form hydrophobic surface layer and retard hydrogen bonding between wood and cement. Phenolic compounds such as tannins have a capacity to combine with metal ions in cement and thus inhibit normal hydration (Bash and Rakhimbaev 1973). The results obtained are consistent with the hydration characteristics results of the untreated materials. Bagasse particles attained the highest extractives content (16.81 %) followed by cotton stalks (12.05 %) and then sunt sawdust (5.44 %). In bagasse the presence of high amounts of soluble extracts and perhaps some waxes in the rind of sugar cane residues might have contributed to this result. For cotton stalks, the presence of high amounts of bark material which may contain hydrolysable tannins beside some water soluble materials might have caused this. In addition to this the extraction technique used had a stage of hot water extraction in it. This might have increased the solubility of more carbohydrates. Sunt sawdust has had a lot of Acacia nilotica bark because the logs are not usually debarked. The bark of this tree species is famous of its high tannins contents. It contains about 15 to 20 percent (Haroun, 1995). Hydrolysable tannins would have been the major constituents of sunt sawdust extractives. Non-hygroscopic extractives components were reported to have had little effect on exothermic behavior of cement (Miller and Moslemi 1991 b).

4.2.2. Lignin Content
Average values of lignin contents of the three lignocellulosic materials are shown in Table 4.4. The results are consistent with previous research results (Hesch 1973, and Mobarak 1983). It was reported that model compounds representing lignin (Indulin AT) caused an intermediate effect on exothermic behavior of cement (Miller and Moslemi 1991b). Since the lignin content of the three lignocellulosic materials is almost identical, it is more unlikely to have had serious inhibitory effects on hydration characteristics.

4.2.3. Hot water solubility

Hot water solubility results are presented in Table 4.4. Hot water solubility test is a method which provides a measure of tannins, gums, sugars, coloring matter and starches in the wood. It was clear from the table that moderate extraction took place by this method as compared to 1% NaOH method. Hot water solubility of bagasse was the highest (19.17%), followed by cotton stalks (17.23) then sunt sawdust (7.41%). When the three lignocellulosic materials were treated with hot water and when no accelerator was added, still depressed the hydration temperature. A slight increase in the maximum hydration temperature was observed with cotton stalks and sunt sawdust from 35.9 °C to 47 °C and from 36.73 °C to 48.48 °C, respectively. No noticeable increase was observed for bagasse. This may be due to the presence of some amounts of hemicellulosic compounds such as xylans, acetic acids and glucose (simple sugars) or quercetin dehydrate (tannin). These compounds are predominantly found in hardwoods hemicelluloses and extractives. They are believed to have had a substantial inhibitory effect on cement exothermic behavior by decreasing the intensity and amount of heat generation (Miller and Moslemi 1991b).

4.2.4. Sodium hydroxide solubility
Table 4.4 shows average values of 1% NaOH solubility of the three lignocellulosic materials used. Hot alkali extracts low molecular weight carbohydrates consisting mainly of hemicelluloses and degraded cellulose in wood (ASTM 1989). The highest values extracted by the weak alkali were observed with bagasse 42.43 %, followed by cotton stalks (34.8 %) and the lowest values were with the sunt sawdust 22.56 %. This result compares favorably with the rise in maximum hydration temperature due to the effect of 1% NaOH with and without additive for sunt and cotton stalks mixtures. The higher solubility of bagasse in the 1% sodium hydroxide solution could be due to removal of more carbohydrates. Even though, the maximum hydration temperature was not enhanced before the addition of calcium chloride. This result indicates that the removal of highly inhibitory substances such as low molecular weight carbohydrates with a drastic extractive method (NaOH) needs further acceleration to render bagasse compatible with cement.
Table 4.4. Average values of chemical analysis of the three lignocellulosic materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Extractives contents %</th>
<th>Lignin %</th>
<th>Hot water solubility (HWS)</th>
<th>NaOH solubility (NHS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>HWS %</td>
<td>pH %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>pH %</td>
<td>NHS %</td>
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<tr>
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<td></td>
<td>pH %</td>
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</tr>
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<td>19.17 a</td>
<td>5.53 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a</td>
<td></td>
<td>42.43 a</td>
</tr>
<tr>
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<td>12.97 a</td>
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<td>12.05 b</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12.86 a</td>
</tr>
<tr>
<td>Sunt</td>
<td>5.44 c</td>
<td>22.5</td>
<td>7.41 c</td>
<td>5.87 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a</td>
<td></td>
<td>22.56 c</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12.48 a</td>
</tr>
</tbody>
</table>

* Means with the same letters in columns are not significantly different (P= 0.0001).

4.3. Effect of Mixing the Three Lignocellulosic Materials on the Properties of Cement Bonded Particleboard
4. 3.1. Physical properties

Compiled average properties of cement bonded particleboard made of different lignocellulosic mixtures and cement wood ratios are listed in Tables 4.5, 4.6, 4.7 and 4.8. As shown in the tables, small variations existed between the planned (nominal) and estimated (observed) densities of the experimental boards. The probable cause of variation could be attributed to the human error introduced during the mat formation. It was not technically possible to ensure evenly distributed furnish materials with the manual felting. These tables show that mean water absorption percent (WA %) and thickness swelling percent (T S %) values for both the 2-hours and the 24-hours water soaking test conform favorably to figures reported in past studies. Badejo (1988), compiled averages that ranged from 32.95 to 46 % and 0.35 to 5.47 for water absorption and thickness swelling tests respectively. Prestmon (1976) reported mean water absorption range values of 28.08 to 65.77 % for 25 mm thick cement bonded particleboards following 24 hours soak in cold water.
Table 4.5 Averages Density, Water absorption and Thickness swelling for cement bonded particleboard made from mixtures of lignocellulosic materials at a cement/wood ratio of 2.5:1.

<table>
<thead>
<tr>
<th>Board type*</th>
<th>Observed density (g/cm³)</th>
<th>WA₂ %</th>
<th>WA₂₄ %</th>
<th>TS₂ %</th>
<th>TS₂₄ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>M 1</td>
<td>1.08</td>
<td>42.4</td>
<td>43.76</td>
<td>11.64</td>
<td>13.1</td>
</tr>
<tr>
<td>M 2</td>
<td>1.06</td>
<td>23.12</td>
<td>28.46</td>
<td>2.88</td>
<td>3.49</td>
</tr>
<tr>
<td>M 3</td>
<td>1.29</td>
<td>17.34</td>
<td>19.29</td>
<td>0.92</td>
<td>1.51</td>
</tr>
<tr>
<td>M 4</td>
<td>1.16</td>
<td>17.61</td>
<td>20.34</td>
<td>1.93</td>
<td>3.77</td>
</tr>
<tr>
<td>M 5</td>
<td>1.24</td>
<td>18.02</td>
<td>19.78</td>
<td>0.99</td>
<td>1.63</td>
</tr>
<tr>
<td>M 6</td>
<td>1.23</td>
<td>20.37</td>
<td>22.24</td>
<td>2.45</td>
<td>3.94</td>
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<td>M 7</td>
<td>1.20</td>
<td>19.51</td>
<td>22.25</td>
<td>1.73</td>
<td>2.75</td>
</tr>
<tr>
<td>M 8</td>
<td>1.31</td>
<td>12.93</td>
<td>15.78</td>
<td>1.9</td>
<td>3.37</td>
</tr>
<tr>
<td>M 9</td>
<td>1.09</td>
<td>31.35</td>
<td>33.37</td>
<td>2.96</td>
<td>4.33</td>
</tr>
</tbody>
</table>

*Mixtures here are the ones given in Table 3.1

Legend:

WA₂ = Water absorption after two hours soaking.
WA₂₄ = Water absorption after 24 hours soaking.
TS₂ = Thickness swelling after 2 hours soaking.
TA₂₄ = Thickness swelling after 24 hours soaking.
Figure 4.14. Mean values of water absorption after two hours (WA₂) for different board types of cement bonded particleboard (CBP), at cement/wood ratio 2.5:1.
- Bars with the same letters are not significantly different.

Figure 4.15. Mean values of water absorption after twenty-four hours (WA₂₄) for different board types of cement bonded particleboard (CBP), at cement/wood ratio 2.5:1.
* Bars with the same letters are not significantly different from each other according to Duncan's test.
Figure 4.16. Mean values of Thickness Swelling % after two hours water soaking (TS2%) for cement bonded particleboard (CBP), at cement/wood ratio 2.5:1.
*Bars with the same letters are not significantly different.

Figure 4.17. Mean values of Thickness Swelling after twenty-four hours water soaking (TS24 %) for cement bonded particleboard (CBP), at cement/wood ratio 2.5:1.
* Bars with the same letters are not significantly different.
Table 4.6 Average Water Absorption, Thickness Swelling and MOR for Cement Bonded Particleboard made from mixtures of three lignocellulosic materials at a cement/wood ratio of 3:1.

<table>
<thead>
<tr>
<th>Board type*</th>
<th>Observed density (g/cm³)</th>
<th>MOR (Kg/cm²)</th>
<th>WA₂ %</th>
<th>WA₂₄ %</th>
<th>TS₂ %</th>
<th>TS₂₄ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>1.3</td>
<td>36.87</td>
<td>25.91</td>
<td>27.15</td>
<td>2.85</td>
<td>4.36</td>
</tr>
<tr>
<td>M2</td>
<td>1.22</td>
<td>31.48</td>
<td>23.69</td>
<td>26.27</td>
<td>3.36</td>
<td>4.86</td>
</tr>
<tr>
<td>M3</td>
<td>1.47</td>
<td>103.21</td>
<td>11.59</td>
<td>13.28</td>
<td>1.33</td>
<td>1.5</td>
</tr>
<tr>
<td>M4</td>
<td>1.19</td>
<td>18.93</td>
<td>31.70</td>
<td>34.09</td>
<td>2.79</td>
<td>3.46</td>
</tr>
<tr>
<td>M5</td>
<td>1.24</td>
<td>22.84</td>
<td>23.80</td>
<td>25.34</td>
<td>2.94</td>
<td>3.75</td>
</tr>
<tr>
<td>M6</td>
<td>1.29</td>
<td>34.05</td>
<td>16.95</td>
<td>19.98</td>
<td>1.81</td>
<td>2.7</td>
</tr>
<tr>
<td>M7</td>
<td>1.22</td>
<td>32.11</td>
<td>23.44</td>
<td>25.19</td>
<td>1.51</td>
<td>2.57</td>
</tr>
<tr>
<td>M8</td>
<td>1.22</td>
<td>13.55</td>
<td>26.89</td>
<td>29.36</td>
<td>1.58</td>
<td>2.72</td>
</tr>
<tr>
<td>M9</td>
<td>1.15</td>
<td>5.98</td>
<td>32.86</td>
<td>34.80</td>
<td>3.40</td>
<td>5.56</td>
</tr>
</tbody>
</table>

* Mixtures here are the ones given in Table 3.1.

Legend:

MOR = Modulus of rupture.  
WA₂ = Water absorption after two hours soaking.  
WA₂₄ = Water absorption after 24 hours soaking.  
TS₂ = Thickness swelling after 2 hours soaking.  
TA₂₄ = Thickness swelling after 24 hours soaking.
Figure 4.18. Mean values of Water absorption percent after two hours water soaking (WA2%) for cement bonded particleboard (CBP) types at cement/wood ratio 3:1. 
*Bars with the same letters are not significantly different.

Figure 4.19. Mean values of Water absorption percent after twenty four hours water soaking (WA24%) for cement bonded particleboard (CBP) types at cement/wood ratio 3:1. 
*Bars with the same letters are not significantly different.
Figure 4.20. Mean values of Thickness Swelling % after two hours water soaking (TS2\%) for cement bonded particleboard (CBP), at cement/wood ratio 3:1.

*Bars with the same letters are not significantly different.

Figure 4.21. Mean values of thickness swelling after twenty four hours water soaking (TS24\%) for cement bonded particleboard (CBP), at cement/wood ratio 3:1.

* Bars with the same letters are not significantly different.
Table 4.7. Average Water absorption, Thickness swelling and MOR for Cement Bonded Particleboard made from mixtures of three lignocellulosic materials at a cement /wood ratio of 3.5:1.

<table>
<thead>
<tr>
<th>Board type*</th>
<th>Observed density(g/cm³)</th>
<th>MOR Kg/cm²</th>
<th>WA₂ %</th>
<th>WA₂₄ %</th>
<th>TS₂ %</th>
<th>TS₂₄ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>1.17</td>
<td>9.18</td>
<td>33.29</td>
<td>34.31</td>
<td>2.59</td>
<td>4.3</td>
</tr>
<tr>
<td>M2</td>
<td>1.15</td>
<td>16.66</td>
<td>20.97</td>
<td>23.84</td>
<td>2.11</td>
<td>3.73</td>
</tr>
<tr>
<td>M3</td>
<td>1.32</td>
<td>35.0</td>
<td>15.37</td>
<td>16.95</td>
<td>1.78</td>
<td>3.59</td>
</tr>
<tr>
<td>M4</td>
<td>1.08</td>
<td>18.29</td>
<td>32.06</td>
<td>33.39</td>
<td>0.99</td>
<td>3.14</td>
</tr>
<tr>
<td>M5</td>
<td>1.27</td>
<td>18.54</td>
<td>20.06</td>
<td>21.34</td>
<td>0.93</td>
<td>1.56</td>
</tr>
<tr>
<td>M6</td>
<td>1.28</td>
<td>23.92</td>
<td>17.80</td>
<td>19.73</td>
<td>1.45</td>
<td>1.97</td>
</tr>
<tr>
<td>M7</td>
<td>1.25</td>
<td>17.03</td>
<td>20.88</td>
<td>22.07</td>
<td>0.73</td>
<td>1.90</td>
</tr>
<tr>
<td>M8</td>
<td>1.23</td>
<td>15.70</td>
<td>20.83</td>
<td>22.91</td>
<td>2.28</td>
<td>3.71</td>
</tr>
<tr>
<td>M9</td>
<td>1.27</td>
<td>15.47</td>
<td>23.74</td>
<td>25.82</td>
<td>2.1</td>
<td>3.61</td>
</tr>
</tbody>
</table>

* Mixtures here are the ones given in Table 3.1.

Legend:

MOR= Modulus of rupture.
WA₂= Water absorption after two hours soaking.
WA₂₄= Water absorption after 24 hours soaking.
TS₂= Thickness swelling after 2 hours soaking.
TA₂₄= Thickness swelling after 24 hours soaking.
Figure 4.22. Mean values of Water absorption percent after two hours water soaking (WA2 %) for cement bonded particleboard (CBP) types at cement/wood ratio 3.5:1.
* Bars with the same letters are not significantly different.

Figure 4.23. Mean values of Water absorption percent after twenty-four hours water soaking (WA24 %) for cement bonded particleboard (CBP) types at cement/wood ratio 3.5:1.
* Bars with the same letters are not significantly different.
Figure 4.24. Mean values of Thickness swelling % after two hours water soaking (TS2%) for cement bonded particleboard (CBP), at cement/wood ratio 3.5:1.
*Bars with the same letters are not significantly different.

Figure 4.25. Mean values of thickness swelling after twenty four hours water soaking (TS24%) for cement bonded particleboard (CBP), at cement/wood ratio 3.5:1.
* Bars with the same letters are not significantly different.
Table 4.8 Average Water Absorption, Thickness Swelling and MOR for Cement Bonded Particleboard made from mixtures of three lignocellulosic materials at a cement /wood ratio of 4:1.

<table>
<thead>
<tr>
<th>Board type*</th>
<th>Observed density (g/cm³)</th>
<th>MOR Kg/cm²</th>
<th>WA₂ %</th>
<th>WA₂₄ %</th>
<th>TS₂ %</th>
<th>TS₂₄ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>1.34</td>
<td>10.32</td>
<td>21.13</td>
<td>22.7</td>
<td>0.68</td>
<td>1.28</td>
</tr>
<tr>
<td>M2</td>
<td>1.18</td>
<td>19.71</td>
<td>15.95</td>
<td>20.5</td>
<td>0.94</td>
<td>1.75</td>
</tr>
<tr>
<td>M3</td>
<td>1.36</td>
<td>32.09</td>
<td>12.79</td>
<td>14.05</td>
<td>0.46</td>
<td>1.08</td>
</tr>
<tr>
<td>M4</td>
<td>1.17</td>
<td>16.15</td>
<td>22.33</td>
<td>23.97</td>
<td>0.42</td>
<td>0.91</td>
</tr>
<tr>
<td>M5</td>
<td>1.28</td>
<td>12.37</td>
<td>19.22</td>
<td>20.01</td>
<td>0.61</td>
<td>1.31</td>
</tr>
<tr>
<td>M6</td>
<td>1.36</td>
<td>20.03</td>
<td>12.24</td>
<td>14.57</td>
<td>0.66</td>
<td>1.46</td>
</tr>
<tr>
<td>M7</td>
<td>1.37</td>
<td>19.97</td>
<td>13.96</td>
<td>15.45</td>
<td>1.67</td>
<td>2.51</td>
</tr>
<tr>
<td>M8</td>
<td>1.3</td>
<td>25.38</td>
<td>16.48</td>
<td>18.58</td>
<td>1.42</td>
<td>1.81</td>
</tr>
<tr>
<td>M9</td>
<td>1.37</td>
<td>24.39</td>
<td>15.02</td>
<td>16.51</td>
<td>0.98</td>
<td>1.38</td>
</tr>
</tbody>
</table>

* Mixtures here are the ones given in Table 3.1.

Legend:

MOR = Modulus of rupture.
WA₂ = Water absorption after two hours soaking.
WA₂₄ = Water absorption after 24 hours soaking.
TS₂ = Thickness swelling after 2 hours soaking.
TA₂₄ = Thickness swelling after 24 hours soaking.
These tables show that mean water absorption percent (WA%) and thickness swelling percent (TS %) values for both the 2-hours and the 24-hours water soaking test conform favorably to figures reported in past studies. Badejo (1988), compiled averages that ranged from 32.95 to 46 % and 0.35 to 5.47 for water absorption and thickness swelling tests respectively. Prestmon (1976) reported mean water absorption range values of 28.08 to 65.77 % for 25 mm thick cement bonded particleboards following 24 hours soaking in cold water. Mean thickness swelling range values of 0.67 to 3.60% was similarly reported in the same study. Dinwoodie (1978) also reported average thickness swelling values of 0.75 % for cement bonded particleboard after soaking in water for 24 hours. The analysis of variance for water absorption after two and twenty four hours (WA2 and WA24) is highly significant (P= 0.0001) for all the mixes and ratios used. The values for the ratio 2.5:1 ranged between 12.93 to 42.4 % for (WA2) and from 15.78 to 43.76 % for (WA24). Mean thickness swelling values for the same ratio 2.5:1 were 3.04 % for (TS2) and 4.20 % for (TS24). The board type (M8) in the ratio 2.5:1 attained the lowest water absorption after 2 hours soaking 12.93 % and the board type (M1) attained the highest value of the same test 42.39 %. This trend was the same for the (WA24) values of the same ratio.
Figure 4.26. Mean values of Water absorption percent after two hours soaking (WA2%) for cement bonded particleboard (CBP) types at cement/wood ratio 4:1.

*Bars with the same letters are not significantly different.

Figure 4.27. Mean values of Water absorption percent after twenty-four hours soaking (WA24%) for cement bonded particle board (CBP) types at cement/wood ratio 4:1.

*Bars with the same letters are not significantly different.
Table 4.9 Minimum and maximum values of water absorption (WA) and thickness swelling (TS) for the different board types by cement/wood (C/W) ratio

<table>
<thead>
<tr>
<th>C/W Ratio</th>
<th>Min. WA₂ %</th>
<th>Max. WA₂ %</th>
<th>Min. WA₂₄ %</th>
<th>Max. WA₂₄ %</th>
<th>Min. TS₂ %</th>
<th>Max. TS₂ %</th>
<th>Min. TS₂₄ %</th>
<th>Max. TS₂₄ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5:1</td>
<td>12.93 (M8)</td>
<td>42.4 (M1)</td>
<td>15.78 (M8)</td>
<td>43.76 (M1)</td>
<td>0.92 (M3)</td>
<td>1.64 (M1)</td>
<td>1.51 (M3)</td>
<td>13.05 (M1)*</td>
</tr>
<tr>
<td>3:1</td>
<td>11.59 (M3)</td>
<td>32.86 (M9)</td>
<td>13.28 (M3)</td>
<td>34.76 (M9)</td>
<td>1.32 (M3)</td>
<td>3.4 (M3)</td>
<td>1.5 (M3)</td>
<td>5.56 (M9)</td>
</tr>
<tr>
<td>3.5:1</td>
<td>15.37 (M3)</td>
<td>33.29 (M1)</td>
<td>16.95 (M3)</td>
<td>34.31 (M1)</td>
<td>0.73 (M7)</td>
<td>2.59 (M1)</td>
<td>1.56 (M5)</td>
<td>4.3 (M1)</td>
</tr>
<tr>
<td>4:1</td>
<td>12.25 (M6)</td>
<td>22.33 (M4)</td>
<td>14.05 (M3)</td>
<td>23.97 (M4)</td>
<td>0.42 (M7)</td>
<td>1.67 (M4)</td>
<td>0.91 (M7)</td>
<td>2.51 (M7)</td>
</tr>
</tbody>
</table>

* Figures in parentheses are board types corresponding to water absorption and thickness swelling values.
Table 4.9 shows the minimum and maximum water absorption and thickness swelling values attained by different board types and ratios. It is clear from the figures in the table that minimum water absorption and thickness swelling values were always associated with board types having higher proportions of a material with high density (sunt). On the other hand the maximum water absorption and thickness swelling figures were associated with board types having greater proportion of a low density material (bagasse or cotton stalks). Presumably this is one of the implications of raw materials' density on board properties. In the mixtures where sunt is a predominant component, thickness swelling and water absorption are reduced. This may be due to the presence of non hygroscopic extractives which may be found in sunt, that serve as dimensional stabilizing agent, by either bulking the wood structure or limiting the absorption of water (Anderson et al.1974 and Kelly 1977).

Table 4.10 shows the overall means of water absorption (WA) and thickness swelling (TS) for cement bonded particleboards for the nine types of board mixtures in each cement / wood ratio. It is clear from the table that, the water absorption values for the ratios 3:1, 3.5:1 and 4:1 decreased with increasing cement to wood ratio. The values of water absorption for the ratio 2.5:1 are the exception. They are slightly lower than the value of the ratio 3:1 and similar to the value of the ratio 3.5:1. This may be due to the higher amount of pressure given to the boards of this ratio during fabrication (27.8 Kg/cm²). This amount of pressure was needed for this low ratio of cement/wood mixture to compress it to the desired thickness. Presumably when mixes of low cement / wood ratios are compressed, higher relative inter-particle contact, will lead to better bond between particles.
The mean values for thickness swelling as shown on Table 4.10, decreased with the increase of cement to wood ratio. The highest values were observed with the 2.5:1 ratio and the lowest were seen with the ratio of 4:1. For the mean separation test and Duncan's grouping of the water absorption and thickness swelling properties see Figures 4.14, 4.15, 4.16, 4.17, 4.18, 4.19, 4.20, 4.21, 4.22, 4.23, 4.24, 4.25, 4.26, 4.27, 4.28, and 4.29. For the analysis of variance table for the properties of cement bonded particleboard at the cement/wood (C/W) ratio 4:1, see Appendix (4).

Table 4.10. Mean Water Absorption (WA) and Thickness swelling (TS) values for cement bonded particleboards for all sets of board types by cement/wood (C/W) ratio.

<table>
<thead>
<tr>
<th>(W/C) Ratio</th>
<th>M.C.%</th>
<th>Density g/cm³</th>
<th>WA₂ (%)</th>
<th>WA₂₄ (%)</th>
<th>TS₂ (%)</th>
<th>TS₂₄ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5:1</td>
<td>12.61</td>
<td>1.19</td>
<td>22.51</td>
<td>25.03</td>
<td>3.04</td>
<td>4.2</td>
</tr>
<tr>
<td>3:1</td>
<td>11.04</td>
<td>1.26</td>
<td>24.09</td>
<td>26.16</td>
<td>2.4</td>
<td>3.5</td>
</tr>
<tr>
<td>3.5:1</td>
<td>10.04</td>
<td>1.22</td>
<td>22.78</td>
<td>24.48</td>
<td>1.66</td>
<td>3.05</td>
</tr>
<tr>
<td>4:1</td>
<td>11.59</td>
<td>1.3</td>
<td>16.57</td>
<td>18.48</td>
<td>0.87</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Figure 4.28. Mean values of Thickness swelling percent after two hours water soaking (TS$_2$ %) for cement bonded particleboard (CBP) at cement/wood (C/W) ratio 4:1.
* Bars with the same letters are not significantly different.

Figure 4.29. Mean values of Thickness swelling percent after twenty-four hours water soaking (TS$_{24}$ %) for cement bonded particleboard (CBP) at cement/wood (C/W) ratio 4:1.
* Bars with the same letters are not significantly different.
4.3.2. Static bending

Averages of modulus of rupture (MOR) for cement bonded particleboards of three sets of nine panel types with different cement to wood ratios; 3:1, 3.5:1 and 4:1 are shown in Tables 4.6, 4.7, and 4.8. The average MOR values of the ratio 3:1 are generally higher than the average values of the ratios 3.5:1 and 4:1. This result is in agreement of the findings reported by Moslemi and Pfister (1987). They indicated that all MOR values are inversely related to cement / wood ratio in the case of type 1 cement (Ordinary Portland Cement).

The MOR of 100% sunt wood-cement boards (M3) of the ratio 3:1 surpassed all other boards in all ratios used. The MOR of sunt-cement mixture of the ratio 3:1 attained an average value of 103.214 Kg/cm² (10.12 MPa) which was the highest among all the boards made in all ratios. This MOR value compares favorably with past research results. Sudin and Ibrahim (1989) reported that the Malaysian standard (MS934) specifies a minimum requirement of 9.0 MPa for bending strength. This MOR of board type (M3) is a very high value in comparison to the boards manufactured in this experiment. This may be attributed to the fairly longer relative pressing time which was held for about six hours. It was intended to be held for 24 hours as prescribed in the literature. A drastic drop in pressure was experienced due to a defective oil seal. The pressing conditions were then changed for the rest of the fabricated panels. The panels in the moulds are pressed for 3-4 minutes in the Carver press then released and clamped overnight in a locally made clamp. (M1) of this ratio also shows a relatively high value of MOR and this again can be attributed to the long pressing time which it happened to be the same as for (M3) of ratio 3:1. It was observed that the boards with high
proportions of sunt wood in the mixture attained higher MOR values in comparison to other mixtures. The MOR values in the ratios 3.5:1 and 4:1 of all board types are generally low. This may be due to the higher cement/wood ratios and the use of calcium chloride. It was reported by some researchers that reduction of the cement to wood ratio increased the bending strength (Moslemi and Pfister 1987) and when calcium chloride was used lower bending strength was observed (Sudin and Ibrahim 1989). It also seems that suitable boards restraining while being set is vital for bond formation. The boards made of 100 % sunt-cement mixture in these ratios still hold onto the lead for MOR values. The analysis of variance for MOR of all set of boards and with all ratios is highly significant at (0.0001) level of probability. For mean separation tests and Duncan's groupings for the variable MOR see the Figures 4.30, 4.31, 4.32, and 4.33. Appendixes (5-7) shows the analysis of variance tables for MOR of the laboratory made cement bonded boards.
Figure 4.30. Mean values of modulus of rupture (MOR) for cement-bonded particleboard (CBP) for the cement/wood ratios (C/W) 3:1, 3.5:1 and 4:1.
* Bars with the same letters are not significantly different.

Figure 4.31. Mean values of modulus of rupture (MOR) of cement bonded particleboard (CBP) made from mixtures of cement and lignocellulosic materials at cement/wood (C/W) ratio 3:1.
* Bars with the same letters are not significantly different.
Figure 4.32. Mean values of modulus of rupture (MOR) of cement bonded particleboards (CBP) made from mixtures of cement and lignocellulosic materials at cement/wood (C/W) ratio 3.5:1.

* Bars with the same letters are not significantly different.

Figure 4.33. Mean values of modulus of rupture (MOR) of cement bonded particleboards (CBP) made from mixtures of cement and lignocellulosic materials at cement/wood (C/W) ratio 4:1.

* Bars with the same letters are not significantly different.
4.4. Effect of Mixing the Three Lignocellulosic Materials on the Properties Resin Bonded Particleboard

4.4.1. Physical properties

Table 4.11 shows the results of the property testing of resin bonded particleboard. It reveals that the average thickness swellings after two hours soaking are rather higher in comparison with past research results.

Table 4.11 Properties of resin bonded particleboard made from mixtures of wood and non-wood lignocellulosic materials.

<table>
<thead>
<tr>
<th>Board Type *</th>
<th>Mechanical properties N/mm² (M pa)</th>
<th>Water absorption %</th>
<th>Thickness swelling %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MOR</td>
<td>MOE</td>
<td>IB</td>
</tr>
<tr>
<td>M1</td>
<td>18.82</td>
<td>5895.39</td>
<td>0.6</td>
</tr>
<tr>
<td>M2</td>
<td>10.58</td>
<td>3017.88</td>
<td>0.74</td>
</tr>
<tr>
<td>M3</td>
<td>16.56</td>
<td>5372.79</td>
<td>1.99</td>
</tr>
<tr>
<td>M4</td>
<td>15.93</td>
<td>3506.17</td>
<td>1.28</td>
</tr>
<tr>
<td>M5</td>
<td>21.73</td>
<td>5616.98</td>
<td>1.68</td>
</tr>
<tr>
<td>M6</td>
<td>19.66</td>
<td>4463.12</td>
<td>1.52</td>
</tr>
<tr>
<td>M7</td>
<td>16.46</td>
<td>4074.96</td>
<td>1.48</td>
</tr>
<tr>
<td>M8</td>
<td>16.17</td>
<td>2862.65</td>
<td>0.89</td>
</tr>
<tr>
<td>M9</td>
<td>18.27</td>
<td>2199.05</td>
<td>1.21</td>
</tr>
<tr>
<td>M10</td>
<td>21.32</td>
<td>3511.53</td>
<td>0.9</td>
</tr>
</tbody>
</table>

*Board types from M1-M9 homogeneous. M10 layered.
The smallest value for thickness swelling after 2-hours water soaking test was observed with the layered board type (M10). The face and back layers of this board type are made from a mixture of equal weights of bagasse (25%) and sunt (25%) particles. The core layer is made from cotton stalk particles (50%).

The amount of thickness swelling attained by the board type (M10) is 7.14%. This result complies favorably with the specifications outlined in the latest European standard (EN 312: 2003). Perhaps the smaller thickness swelling of this particular board type is due to the layering of the board. The smaller particles of the face and back layers may have restrained the swelling of the coarser cotton stalk particles. Another possible reason is that the lignin in the face and back layers may have been plasticized and hardened by the heat of the platens and therefore acts as a barrier. The highest thickness swelling was observed with the 100% bagasse boards (M1). Bagasse boards were anticipated to absorb more water than other boards. The values of thickness swelling after 24 hours compares favorably with most of the previous research results of EL Osta et al. (1991) and Turreda (1983). The smallest values were observed in the 100% sunt board type (M3) and the layered board type (M10). In the mixtures where sunt is a predominant component, thickness swelling and water absorption are reduced. This may be due to the presence of non hygroscopic extractives which may be found in sunt, that serve as dimensional stabilizing agent, by either bulking the wood structure or limiting the absorption of water (Anderson et al. 1974 and Kelly 1977).

The analysis of variance showed that the variation in thickness swelling was highly significant (P= 0.0001). Figures 4.34 and 4.35 show the mean values of the thickness swellings at two and twenty four hours water soaking tests as well as the Duncan's grouping. Water absorption values after 2-hours soaking test are similar to the figures reported by Turreda
(1988), and EL-Osta et al. (1988) but they are higher than the results reported by EL-Osta et al. (1991). The smallest value (18.5) is attained by board type (M8) which is a mixture of 50% cotton stalks particles and 25% for each of bagasse and sunt sawdust particles. The highest WA$_2$ value (47.72%) was observed in board type (M2) which is 100% cotton stalk particles.

Water absorption values after 24-hours soaking test (WA$_{24}$) are higher than the values obtained by El-Osta et al. (1991) for a layered particleboard from a mixture of Casuarina wood and flax shives. They reported (WA$_{24}$) values ranging between (24.3% and 35.7 %). The (WA$_{24}$) values obtained from the boards under investigation are similar to the values reported by EL-Osta et al. (1988) from particleboard made from Casuarina flakes (mean WA$_{24}$ value of 61.4%). The highest WA$_{24}$ value (69.6%) was observed in board type (M2) which is 100% cotton stalks panel. This may be attributed to the larger internal voids because of large particle sizes (Gertjejansen, 1978).

The lower values of water absorption attained by boards type (M8), and the relatively low TS values could be attributed to the modified fabrication conditions of this particular board type. Several attempts using ordinary fabrication conditions described in materials and methods, produced boards with split core layers. Among the successful manipulation factors was the reduction of mat moisture content (from 13% to 8%), addition of more resin (slightly greater than 10%), increased pressing time, and better resin blending.
Figure 4.34. Mean values of Thickness swelling percent after two hours water soaking (TS2 %) for resin-bonded particleboard types, made from different mixtures of three lignocellulosic materials.
*Bars with the same letters are not significantly different.

Figure 4.35. Mean values of Thickness swelling percent after twenty-four hours water soaking (TS24%) for resin bonded particleboard types made from different mixtures of three lignocellulosic materials.
* Bars with the same letters are not significantly different.
Figure 4.36. Mean values of Water absorption percent after two hours water soaking for different resin bonded board types made from mixtures of three lignocellulosic materials.
* Bars with the same letters are not significantly different

Figure 4.37. Mean values of Water absorption percent after twenty-four hours water soaking for different resin bonded board types made from mixtures of three lignocellulosic materials.
* Bars with the same letters are not significantly different
The analysis of variance revealed that the differences in thickness swelling (TS) and water absorption (WA) for both the two and twenty-four hours soaking tests, were highly significant at (P= 0.0001). Figures, 4.34, 4.35, 4.36 and 4.37 show the mean separation test and Duncan's grouping of the variables TS2, TS24, WA2, WA24, respectively. Appendix (6) shows the results of analysis of variance for the same properties (WA2, WA24, TS2, and TS24).

4.4.2. Mechanical properties

The averages of strength and dimensional stability properties of particle board made from different mixtures of wood and non-wood lignocellulosic materials are presented in Table 4.11. The values of modulus of rupture (MOR) and modulus of elasticity (MOE) are in line with previous research results of Gertjejansen (1977), Turreda (1983), Klozlowski et al. (1994) and EL-Osta et al. (1991). Nine out of ten MOR values of the boards made, comply with the specifications of European standard (EN 312: 2003). They fulfilled the requirement for general purpose boards for use in dry conditions (Type p1), for interior fittings (including furniture) for use in dry conditions (Type p2). Also they meet the requirements for non-load bearing boards for use in humid conditions (p3) and for load bearing boards for use in dry conditions (Type 4). The only one board type which is below this standard is type (M2) which is 100 % cotton stalks particles. The highest MOR value (21.73 MPa) observed with board type (M5), followed by board type (M10) with (21.3 MPa). The lowest MOR value was reported with board type (M2). This low MOR is probably due to the thicker flakes (Vital et al. (1974), Shuler (1976).

MOE values of the entire laboratory fabricated board types are higher than the minimum requirements specified by the EN 312: 2003. Some values are slightly higher than values reported in previous research results
of a similar nature. This can be explained as a result of the smaller observed thicknesses as compared to the targeted thicknesses. Lack of thicknessing valves or suitable stoppers in the press has led to these variations.

The analysis of variance indicated that differences in MOR and MOE were highly significant (P = 0.0001). For mean separation and Duncan's grouping see Figures 4.38 and 4.39. Appendix (8) shows the ANOVA table for MOR and MOE of resin bonded boards.
Figure 4.38. Mean values of Modulus of rupture for resin bonded particleboard types made from different mixtures of three lignocellulosic materials.

* Bars with the same letters are not significantly different.

Figure 4.39. Mean values of Modulus of elasticity for resin bonded particleboard types made from different mixtures of three lignocellulosic materials.

* Bars with the same letters are not significantly different.
The internal bond strength (IB) of all board types exceeded the minimum standard specifications set by EN 312: 2003 for general purpose boards, boards for interior fitments as well as boards intended for load and non-load bearing for use in dry and humid conditions. The highest internal bond values were noticed generally with boards having higher proportions of sunt sawdust. The pure sunt boards (type M3) attained the highest internal bond value which is about 20.31 Kg/cm² (1.99 N/mm²), followed by (type M5), about 17.15 Kg/cm² (1.68 N/mm²). The boards types (M2) and (M1) which were made of 100 % cotton stalks and bagasse particles, attained the lowest values, 7.6 Kg/cm² (0.074 N/mm²) and 6.15 Kg/cm² (0.6 N/mm²), respectively. This could be due to particle geometry, particle distribution and resin distribution. However, as had been mentioned by many researchers, the efficiency of the resin depends on its properties, but its distribution on the particles and its contact with adjacent particles are more practically considered to affect a change in internal bond strength properties in particleboard (Post, 1958, Lehman, 1970, Shuler, 1974 and Generalla et al. (1989). The effect of resin distribution was notable with bagasse particles. Since bagasse is light in weight, its bulky volume in the blender rendered the even distribution of the resin very difficult. Even when reduced volumes are blended in batches, several small balls are usually formed. The analysis of variance showed that the differences in internal bond were highly significant (P = 0.0001). For the Duncan's grouping of the internal bond results, see figure 4.40. ANOVA table for internal bond strength is shown in appendix (8). The properties of boards produced can also be affected by factors other than the type of raw material. Among the major factors
that affect the properties of particleboard are type and size of particles, type and amounts of binder, additive used, mat moisture distribution, mattress structure, board specific gravity and orientation of particles. Almost all of these parameters interact with each other. Thorough investigation of the various factors has led to a continuous improvement of particleboard quality (Kollman et al. 1975).

![Diagram of Internal Bond (IB)](image)

**Figure 4.40.** Mean values of Internal bond (IB) for resin bonded particleboard types made from different mixtures of three lignocellulosic materials.

* Bars with the same letters are not significantly different.
Chapter Five

5.1. Conclusions
Within the limitation of the study, the following conclusions may be drawn:
- The three lignocellulosic materials; bagasse, cotton stalks and sunt sawdust are incompatible with ordinary Portland cement
- The best common treatment which proved effective for enhancing the compatibility of the three lignocellulosic materials was the extraction with 1% NaOH and addition of 3 % CaCl₂ as accelerator.
- Hot water treatment with 3 % CaCl₂ is equally suitable for both sunt sawdust and cotton stalks particles.
- Addition of 3 % CaCl₂ to the untreated sunt sawdust also proved to be a suitable treatment.
- Bagasse is the least responsive among the lignocellulosic materials to the treatments used, followed by cotton stalks, then sunt sawdust.
- Cement-bonded particleboard can be made from the three lignocellulosic materials either pure or mixed in different proportions after weak alkali- treatment and addition of Calcium chloride as accelerator.
- Generally the highest water absorption and thickness swelling values of cement-bonded particleboards are always associated with boards having high proportions of bagasse particles.
- The lowest water absorption and thickness swelling values of cement bonded particleboards are always associated with boards of high proportions of sunt sawdust particles.
- The properties of dimensional stability figures of all the ratios of cement bonded panels produced, comply favorably with past research results.
- The cement / wood ratio (3:1) attained generally the highest Bending strength (MOR) values compared to the other ratios tested (3.5:1 and 4:1).
- Thickness swelling percent (TS %) generally decrease with the increase of cement /wood ratio.
- There appears to be no problem in combining bagasse with sunt wood or with cotton stalks particles or blending those all in different proportions to produce homogeneous or layered resin bonded particleboard.
- The 10 % resin content level of Urea formaldehyde adhesive was found to be suitable for the production of panels with acceptable properties.
- The addition of bagasse particles to sunt sawdust or cotton stalks or to mixtures of them improved the properties of particleboards made of their mixtures.
- The smallest thickness swelling for the two-hour water soaking test was attained by the layered board type (mix 10).
- Generally speaking board properties were influenced by the proportion of the type of furnishes (Percent of bagasse, cotton stalks and sunt particles).
- Minimum property requirements of the European commercial standard EN 312: 2003 for MOR and MOE were met or exceeded by all board types except the board type (M2), which is a 100 % cotton stalks particle.
- Pure resin bonded bagasse boards attained the highest MOR values in comparison with boards made of 100 % sunt or cotton stalks particles under the same manufacturing conditions.

5.2. Recommendations
- For sun sawdust to be used in cement bonded particleboard, the logs should be debarked before conversion into lumber.

- Other cement setting accelerators such as magnesium chloride, and aluminum sulfate should be tried as hardeners for cement to evaluate their effects on MOR and MOE properties.

- Production of layered particleboard types with manipulation of different mixtures of surface and core particles should be tried to see their effect on board properties.

- Testing the effects of some other processing parameters on the properties of boards produced.

- The suitability of other widely cultivated crop residues or any suitable source of lignocellulosic material in the Sudan for cement and resin bonded particleboard manufacture, should be studied to extend the raw material base for this product.

- Evaluate the effect of other binders such as Phenol formaldehyde (PF) and Melamine formaldehyde (MF) on board properties.

- Different glue levels should also be used to study their effect on board properties.
6. Literature cited


Anonymous 1986. MS.934: Malaysian Standard-Specifications for wood cement board; Standard and Industrial Research Institute of Malaysia (SIRIM), Malaysia.


DIN, EN 323.1993 E. Wood–Based panels; Determination of density, European Committee for Standardization.CEN.Central Secretariat: rue de stassart 36, B-1050, Brussels.


EN324-1, 1993. Wood–Based Panels; Determination of dimensions of boards, Part-1: Determination of thickness, width and length, European Committee for Standardization, CEN. Central Secretariat: rue de stassart 36, B-1050, Brussels.


Proceedings of "wood-cement composites in the Asia Pacific Region" a workshop held at Canberra, Australia, on 10 December 2000. pp. 49-54.


Heebink, B.G. 1974. Particleboards from lodgepole pine forest residue. USDA, Forest Service Research Paper, FPL. 221. Forest Products Laboratory, Madison, WIS.


Mohamed, T. E. 1989. Particleboard from Non-Wood Lignocellulosic Materials., A thesis submitted to the University of Wales for the degree of Master of Science, Department of Forestry and wood science, University College of North Wales, Bangor.


Appendices

Appendix (1)

ANOVA table for Maximum hydration temperature.

<table>
<thead>
<tr>
<th>Species</th>
<th>source</th>
<th>DF</th>
<th>ANOVA ss</th>
<th>Mean sq.</th>
<th>F value</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bagasse TRT</td>
<td>5</td>
<td>2151.9894</td>
<td>430.3979</td>
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</tr>
<tr>
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<td>5</td>
<td>2635.68</td>
<td>94527.1379</td>
<td>365.50</td>
<td>0.0001</td>
<td></td>
</tr>
<tr>
<td>Sunt TRT</td>
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<td>2703.0711</td>
<td>540.6142</td>
<td>707.71</td>
<td>0.0001</td>
<td></td>
</tr>
</tbody>
</table>

Appendix (2)

ANOVA table for Time to reach maximum hydration temperature.

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<th>DF</th>
<th>ANOVA ss</th>
<th>Mean sq.</th>
<th>F value</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
</tr>
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<td>Sunt TRT</td>
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<td>600.48978</td>
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</tbody>
</table>

Appendix (3)

ANOVA table for rise in temperature above the ambient.

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<th>Species</th>
<th>source</th>
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<th>ANOVA ss</th>
<th>Mean sq.</th>
<th>F value</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
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<td>Bagasse TRT</td>
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<tr>
<td>Cotton stalks TRT</td>
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<td>2267.645</td>
<td>453.5290</td>
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<td></td>
</tr>
<tr>
<td>Sunt TRT</td>
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<td>2554.4911</td>
<td>510.8982</td>
<td>542.87</td>
<td>0.0001</td>
<td></td>
</tr>
</tbody>
</table>
Appendix (4)

ANOVA table for Water Absorption (WA), Thickness Swelling (TS) for Cement–Bonded Particleboard (CBP) at C/W Ratio 2.5:1

<table>
<thead>
<tr>
<th>Variable</th>
<th>source</th>
<th>DF</th>
<th>ANOVA ss</th>
<th>Mean sq.</th>
<th>F value</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
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<td>Density</td>
<td>Mixtures</td>
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<td>0.412367</td>
<td>0.05155</td>
<td>10.16</td>
<td>0.0001</td>
</tr>
<tr>
<td>WA2</td>
<td>Mixtures</td>
<td>8</td>
<td>3901.6889</td>
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<td>WA24</td>
<td>Mixtures</td>
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<td>3696.3688</td>
<td>462.046</td>
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<td>0.0001</td>
</tr>
<tr>
<td>TS2</td>
<td>Mixtures</td>
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<td>523.3147</td>
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</tr>
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<td>Mixtures</td>
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</tr>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Appendix (5)

ANOVA table for Water Absorption (WA), Thickness Swelling (TS) and MOR for Cement–Bonded Particleboard (CBP) at C/W Ratio 3:1.

<table>
<thead>
<tr>
<th>Variable</th>
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<th>ANOVA ss</th>
<th>Mean sq.</th>
<th>F value</th>
<th>Pr&gt;F</th>
</tr>
</thead>
<tbody>
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<td>Density</td>
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<td>0.40581481</td>
<td>0.050727</td>
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<tr>
<td>WA2</td>
<td>Mixtures</td>
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<td>2122.80837</td>
<td>265.351</td>
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</tr>
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<td>WA24</td>
<td>Mixtures</td>
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<td>2126.41968</td>
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<td>TS2</td>
<td>Mixtures</td>
<td>8</td>
<td>33.281348</td>
<td>4.16017</td>
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<td>TS24</td>
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<td>37.449333</td>
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<td>MOR</td>
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<td>8</td>
<td>19075.489</td>
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</table>

Appendix (6)

ANOVA table for Water Absorption (WA), Thickness Swelling (TS) and MOR for Cement–Bonded Particleboard (CBP) at C/W Ratio 3.5:1.

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<tr>
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</thead>
<tbody>
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<td>0.27636667</td>
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<td>8</td>
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Appendix (7)

ANOVA table for Water Absorption (WA), Thickness Swelling (TS) and MOR for Cement–Bonded Particleboard (CBP) at C/W Ratio 4:1.

<table>
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<tr>
<th>Variable</th>
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</thead>
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</table>

Appendix (8)

ANOVA table for the properties of Resin bonded particleboard.

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<th>ANOVA ss</th>
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<th>F value</th>
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</tr>
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<tbody>
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<td>1237.5875</td>
<td>137.5097</td>
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</tbody>
</table>