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Agro-Waste-Cement Particleboards: A Review

Davies I.O.E, Department of Civil Engineering College Faculty of Engineering, Landmark University, Omu-Aran, Nigeria, davies.iyinoluwa@lmu.edu.ng

Davies O.O.A, Department of Architecture, College of Environmental Sciences, Joseph Ayo Babalola University, Ikeji-Arakeji, Nigeria, daviesoluwadamilola954@gmail.com

Abstrac-**The high rate of demand for forest wood consumption is considered as one of the major factor for the high rate of deforestation as well as degradation impact on the environment which has grave consequent on the global warming. The growing demands for wood-based particleboards have raised serious challenges on the sustainability of raw materials to this sector for some time. However, alternative fibers such as agricultural residues, industrial wastes and non-wood plant fibers could contribute greatly in providing the balance between supply and demand for the production of composite panels like particleboard and fibreboard. This paper provides information on the physical, mechanical, thermal and electrical properties of cement-bonded particleboards produced from industrial and agricultural wastes. Cement-bonded particleboards possess properties such as high moisture resistance and dimensionally stability when subjected to water soaking and may serve as cheap construction material for walls and roofing of houses, high resistance to white-rot and brown-rot fungi and r high resistance to fire. The increase in cement content of the boards and introduction of chemical additives lowers the water absorption and thickness swelling of the boards. Increase in cement content of the boards, pretreatment of lignocellulosic materials and addition of chemical additives significantly influence the particleboard density, internal bonding strength, modulus of rupture, modulus of elasticity, water absorption capacity and compressive strength of the particleboard. This paper provides information on the physical, mechanical, thermal and electrical properties of cement-bonded particleboards produced from industrial and agricultural wastes.**

***Keywords*: Agricultural wastes, adhesive, physical properties, utilization**

I. INTRODUCTION

Particleboard is a wood-based panel produced under pressure and sometimes temperature using wood particles or other lignocellulosic materials and an adhesive [1]. It is commonly used in the production of furniture, floor underlayment, cabinets, stair treads, home constructions, tabletops, vanities, speakers, sliding doors, lock blocks, interior signs, table tennis, pool tables, electronic game consoles, kitchen worktops, and work surfaces in offices, educational establishments, laboratories and some other industrial products [2]. The high rate of demand for forest wood consumption is considered as a main reason for the high rate of deforestation as well as grave impact on the environment which has resulted to global warming. The growing demand for wood-based particleboards have raised serious challenges on the issue regarding the sustained supply of raw materials to this sectors for quite some time [3].However, the need to reduce the dependence on wood and forest resources has resulted in a great interest for alternative resources substitute wood raw material for agricultural residues and wastes for particleboard production.

The alternative fibers such as agricultural residues and non-wood plant fibers could serve as the balance between supply and demand for the manufacturing of composite panels such as particleboard. The need to reduce the dependence on wood and forest resources has gingered interest in the utilization of agricultural residues and wastes for particleboard production. Many researchers have conducted studies on a wide variety of agricultural wastes and residues from many different regions of the world: wheat straws [4-7], rice husks/straws[8], waste grass [9], kenaf[10],betel palm [11], rice bran[12], kiwi pruning [13], cotton carpel [14] and bagasse [15].

Technological development has led to renewed interest in the utilization of industrial and agricultural wastes. It enhances total wastes utilization, reduces cost of production, promotes a cleaner environment and enhances the earning of the farmers. It also prevents burning of agricultural residues and wastes and thus mitigates climate change [16]. Different value added products has been produced from agricultural and industrial wastes. These products have eliminated most of the negative implications posed by indecent disposal and management of wood residues as waste [16].Cement-bonded particleboards have been subjected to different studies with the purpose of using other types of wood or vegetable biomass, as the chemical compounds from wood (extractives and sugars) tend to inhibit of cement hydration. Sellers [17] reported that there is an upsurge in the demand for glued-wood composite products which includes particleboard, medium-density fiberboard and plywood. The adoption of these products for domestic and industrial utilizations such as housing construction and furniture production has since been used in most of the developed and developing countries of the world. Increase in awareness on the benefits of commercial production of cement-bonded composites made from agricultural and industrial wastes enhanced low-cost housing projects in the developing countries.

Wood–cement composites is not new but have been used in the production of construction materials for more than 60 years. They have the potential to provide a wide range of products for building applications by using different forms of wood-based materials. The development and application of wood–cement composites attest to their attraction as building materials [18].Cement is currently being widely utilized for residential and non-residential construction as the basic constituent material for the production of concrete, mortar and cement grout. Cement is predominantly used for the construction of residential building. Increase in the demand for cement has gingered many scientists to explore for substitute material as a replacement of ordinary Portland cement. Several industrial wastes such as slag, silica fume and fly ash are utilized as admixture to reduce the quantity of cement required for a particular project.

Cement-bonded panel boards (cement-bonded particle and fibreboards) have some peculiar characteristics that gave them advantages over other panels for niche applications [19, 20]. They possess properties such as high moisture resistance and dimensionally stability when subjected to water soaking [21] and may therefore serve as cheap construction material for walls and roofing of houses [16]. Due to their high resistance to fire [22], they can act also as a good replacement of asbestos [23, 24]. There is paucity of information on durability of cement and gypsum-bonded particleboards but they have high resistance to white-rot and brown-rot fungi [18]. For applications in residential constructions in climates with frost, resistance against freezing and thawing would need to be improved. Generally for wider ranges of applications, the common observed low quality bonding between cements and some wood species or non-wood fibres based on incompatibilities between the different materials is a challenge to be resolved [25]. This paper provides information on the physical, mechanical, thermal and electrical properties of cement-bonded particleboards produced from industrial and agricultural wastes.

II. SAWDUST AS INDUSTRIAL WASTES FOR PRODUCTION OF PARTICLEBOARDS

A. Sawdust

Sawdust is generated as a by-product of the timber industry but finds limited industrial applications and is mostly discarded or incinerated, causing environmental problems [26]. Sawdust is of two particle sizes (fine and coarse sizes) that are produced from the milling process that involves cutting, grinding, and sanding of boards or planks. Presently, sawdust is useful in the production of particleboards, mulch and fuel briquettes. The weight of sawdust-cement particleboards is heavier than the particleboards produced with organic-bonded particleboards. Sawdust is majorly discharged in landfill due to the development of timber and wood industries for the activity such as furniture manufacture. Predominantly, the particleboard mills are integrated with sawmills for sustainable development and utilization of wood waste [27]. In spite of its enormous potential accredited to wood residue and wastes for the production of particleboards for export and domestic purposes, its production still remained very low. This could be attributed to poor investment incentives [27]. Sawmill industries for a long time has experienced shortfall. Some of the reasons behind the low recovery rate according to Hossain et al. [27] are: sawing techniques being employed, width of the machine kerf for sawing, the variation in sawing variation, size of dry dressed lumber and as well as rough green-lumber size, decision making by sawmill personnel, product mix, maintenance and condition of sawmill equipment, and small log dimension, taper as well as the quality. Fono-Tamo*et al.* [28] reported some physical and mechanical properties of sawdust based particleboard at moisture content 11.89%

III. AGRICULTURAL WASTES FOR PRODUCTION OF PARTICLEBOARDS

The performance and percentage waste generation in the forest industry in Nigeria have undergone critical assessments by a number of authors. Most of the wood processing outfits in the country are usually without facilities for process integration of waste, thus, making it very inefficient in terms of wood conversion. The waste generated is very enormous and the wood processing units lack the facilities for their utilization. The high rate of waste generation is caused by a multitude of factors. The factors responsible differ from one subsector to the other, but a general trend indicated that average percentage volume recovery is getting lower while waste generation is on the increase. This is mainly due to the reduced size of average timber available for processing and the increasing need to utilize lesser used wood species whose properties are not well understood. There is a growing awareness in the production of wood-cement boards from waste wood and other agricultural residues and wastes to protect the environment. The production of particleboard from recycling wastes and as well as recycled products reduces the high demand on forest resource, save energy and reduces environmental degradation. Cement-bonded particleboard is resistance to biological spoilage, insect infestation and fire.

A. Palm kernel shells

The oil palm is grown commercially in Nigeria. Oil palm plant is called domestic plant. It is very rich in oil and Vitamin A. Among all the vegetable oil crops, palm oil yields more oil on per unit area basis. Palm kernel shells as a local material. They are the crushed outer part of palm kernel nut derived after the extraction of palm oil. Palm kernel shell is the hard endocarp of palm kernel fruit that surrounds the palm seed. It is obtained as crushed pieces after threshing or crushing to remove the seed which is used in the production of palm kernel oil [29]. Palm kernel shells are available in large quantities in palm oil producing areas. The characteristics of palm kernel shells include, kernel shells are black in colour, light in weight, porous in nature and very hard among others [30].

Palm kernel shell is also regarded as a by-product from palm oil production which produces large quantities of palm kernel shells annually [28]. From this production, only some amounts are utilized for biofuel for domestic cooking and other applications namely palliative for un-tarred road, in producing activated carbon, used by the blacksmith and goldsmith to make bellow for melting iron and gold, production of terrazzo, as filler materials for filling pot holes in muddy areas in some localities, as light weight aggregate and useful for thermal insulation [31].The leftover palm kernel shells are regarded as waste which litters the processing mill, becoming environmental and economic nuisance to the mill. However, Teo [32] reported the incorporation of palm kernel shells in the production of structural light weight concretes with increased mechanical strength. Fono-Tamo[33] utilized pulverised palm kernel shells in the production of friction material for automotive application. Over the years, these observations have aroused the interest of researchers on production of particleboard from pulverised palm kernel shells.

B. Mechanical, Physical and Thermal Properties of Palm kernel Shells

The mechanical, physical and thermal properties of palm kernel shells that make them useful material for particleboard production are shown in Table 1.

TABLE 1. Physical and Thermal Properties of Palm kernel Shells

Property	PKS Particles Mean Value±SD
Bulk density (kg/m^3)	560±17.4
Specific gravity	1.26±0.07
Thermal conductivity (W/m.K)	0.68±0.05
Specific heat (kJ/kg.K)	1.983±0.10
Phase change (˚C)	101.4

Source: Fono-Tamo and Koya[34]

TABLE 2. Mechanical Properties of Cement and Concrete Composites containing Palm kernel Shells

Biomass	Compressive strength (MPa)	Flexural strength (MPa)	Splitting strength (MPa)	Modulus elasticity (GPa)	References
Palm kernel shells	15.0–25.0	-	-	-	Olanipekun et al. [34]
Oil palm shells	20.1–24.2	-	-	-	MannanandGanapathy [35]
Palm fibers (leaves)	60.2–65.0	9.4–9.9	3.8–4.4	-	Al-Oraimi and Seibi[36]
Oil palm shells	36.70–37.41	-	1.95–2.10	10.05–11.15	Alengaram and Jumaat[37]
Oil palm shells	20.12–24.22	2.75–4.00	1.78–2.41	7.0–7.6	Mannan and Ganapathy[38]
Oil palm shells	42.8–48.3	-	-	-	Shafigh et al. [39]
Oil palm shells	26.98–37.79	-	1.98–22.35	7.08–10.90	Mahmu et al. [40]

Source: Source: Vo and Navard [41]

C. Merits of Palm kernel Particleboards

The swelling rate of particleboard containing palm kernel shell as composite was very low when compared with the wood-based particleboard because the palm kernel shell showed little or no significant swell percentage. This was an indication that palm kernel shell-wood based particleboard will perform better than the ordinary wood-based particleboard when exposed to moisture.

D. Environmental implication of agricultural residues and wastes

Agricultural residues and wastes in most developing countries of the world have very limited reuse capacity and they are dumped indiscriminately or sometimes burnt openly in the field [42]. The implication of this acts have enormous negative environmental consequences such as increased levels of carbon dioxide in the atmosphere, which contributes to global warming. These wastes sometimes block drainage systems and thus cause flooding. The utilization of these wastes primarily will improve environment and socio-economic well being of the people. Due to their abundances nature, the utilization in the production of particleboards will be cheaper and environmental friendly [43, 44].

E. Utilization of agro-wastes for particleboards

Many useful value added products has been manufactured from industrial and agricultural wastes. These products have eliminated most of the adverse effects posed by improper disposal and management of wood residues as mere waste. The increasing in awareness in the possibility of utilization of raw materials in wood composite industries has led scientists to investigate non-wood lignocellulosic biomass utilization in composite production including particleboards in the recent time [42, 45]. In view of the huge quantities of plant fiber and agricultural waste materials annually have become alternative raw materials for particleboard production, and more than 30 plants have been reportedly utilized in their productions around the world [3, 46]. Nemli et al. [9] maintained that alternative raw materials such as agricultural residues will play a major role in the particleboard industry in the future. Studies on particleboards utilizing agricultural and wood residues include cotton stalks [47], hazelnut husk [48], betel palm [11] and kenaf stalks [10], almond shells [49], kenaf core [50], sunflower stalks [51], eggplant stalks [52], waste grass clippings [9] and bagasse [15].

The utilization of industrial and agricultural wastes such as sawdust and palm wastes for production of particleboards could be the best method to encourage total wood utilization, reduce cost of production and enhanced cleaner environment. Enhanced value added products can be made from agricultural and industrial wastes. Wastes utilization has reduced to the barest minimum the negative implications experienced by improper disposal and management of agricultural and wood wastes. Other industrial and agricultural wastes being investigated for their suitability in the production of particleboards include: eucalypt and poplar [25], rattan furniture waste [53], coconut coir [54], coconut husk [55], bagasse: wheat and eucalyptus [56]. The utilization of agricultural and industrial wastes for production of particleboards has the potential to reduce the pressure on forest resources and at the same time provide solutions to the problems of agricultural and industrial wastes disposal in Nigeria. Plates 1 to 2 show composite board from an agro-waste. Table 4 shows the types, sizes and quantities of agricultural waste used in cement and concrete composites.

Plate1.Coconut Reinforced Concretes: a) a concrete block, b) the concrete panels and c) the house built from them

Source: Vo and Navard (2016)[31]

Plate2.2: Various applications of mountain pine wood concretes

Source: Vo and Navard[31]

Table 3. Different Agricultural Wastes used in Cement and Concrete Composites

Agricultural waste	Size (mm)	Water/ binder ratio	Quantity of agricultural waste	References
Oil palm (coconut) shell	5–15(20)	0.5 and 0.75	0–25–50–75–100% of coarse aggregate (stone)	Olanipekun et al. [34]
Oil palm shell (OPS)	Max. 12.5	0.41	Sand/OPS ratio 2.22 by weight	Mannan and Ganapathy[35]
Oil palm shell	1.5–2.5	0.41	0.77 (weight proportion)	. Basri et al.[57]
Palm fibres (21.13 lm)	30 (length)	0.43	0.25–0.5–0.75–1.0 vol%	DawoodandRamli[58]
Palm fibres (leaves)	30 (length)	0.34	0.05 to 0.15 wt% (of total wet solid)	Al-OraimiandSeibi[36]
Date surface palm fibres (around the trunk)	15 and 60	Adjusted to the mix with fibres percentage	Percentage of fibres was varied but the mass of fibres plus aggregates was maintained constant	Kriker et al.[59]
Hemp shives	4–8–9	49–51% (water content)	16–17 wt%	Glé et al.[60]
Hemp fibres, wheat straw, Miscanthus	40	0.67	0.19% by weight (4.5 kg/m^3)	MertaandTschegg[61]
Hemp fibres	30 (length) 0.6 (diameter)	0.68	0–0.5–0.75–1 vol%	Awwad et al. [62]
Coconut shell	Max. 12.5	0.42 to 0.72	Shell/cement ratio = 0.55–0.6–0.65	Gunasekaran et al. [63]

Coconut fibres	25–50–75	0.48	1–2–3–5% by cements mass	Ali et al. [64]
Coconut fibres	20–30 (length) 0.32 (diameter)	0.42	0.6–1.2–1.8–2.4% based on binder volume	Ramli et al.[65]
Coconut shell	Max. 12.5	0.42	332 kg/m^3	Gunasekaran et al. [66]
Flax shives	4–8 (length) 0.6–1.3 (width)	0.5 or 0.75	Shive to cement volume = 4	Khazma et al. [67]Khazma et al. [68] and Khazma et al. [69]
Flax stem fibres	20–30	0.58	0.5 and 1% (v/v)	Snoeck and De Belie [70]
Flax straw fibres	10–19–38		0.05–0.1–0.3% by volume	Boghossian, and Wegner [71]
Eucalyptus kraft pulp	0.81 (length)		5 wt% (or 9 vol%)	Tonol et al.[72]
Sulphite pulp fibres	1.2–1.5	1	5–10–15% by binder mass	Hosseinpourpia et al. [73]
Micro- cellulose fibres (recycling of cardboard)	1.1 (length) 0.045 (diameter)	0.35	14–21–28–41–83–138% volume fractions of fibre to cement	. Mohamed et al.[74]
Wood shaves	0.1–8	0.59	0–160 kg/m^3	Bederina et al. [75]; Bederina et al. [76]; Bederina et al. [77]
Kenafbastfibres	25–38	0.35	1.2–2.4% (volume content)	Elsaid et al.[78]
Lechuguillafibres	25 and 50	1	0.25–0.50–0.75–1.0 (volume fraction)	Juárez et *al*.[79]
Lechuguillafibres	20–30	0.35 and 0.65	1 vol%	Juárez et *al*. [80]

Source: Vo and Navard [31]

IV. WOOD- CEMENT COMPOSITES

Composites are materials composed of a combination of two or more essentially non-miscible constituents that may differ in physical and chemical properties and/or in their structural or geometrical nature. Composite materials present better characteristics than their original constituents [18]. However, the number of possible combinations of constituents, ratios between them, method of bonding, interface interactions, shape and relative orientation, among other variables make a real challenge to predict and design the characteristics of a composite. Particleboards are composite materials.

A. Wood–Organic Adhesive Composites

The synthetic organic adhesives commonly used in the production of particleboard wood based materials are phenols and formaldehydes [81]. However, formaldehyde is declared to be carcinogenic [16, 24]. Based on health concerns, legal restrictions exist for the usage of formaldehyde. Phenol-formaldehyde resins are of significant importance for the panel board industry. It possesses both a high dry and a high wet bonding strength, and a strong adhesion to wood. Phenol-formaldehyde resins have the widest application range of all synthetic resins based on their high adaptability. Their main application field is the production of humidity-resistant particle boards. They are also utilized for the production of weather-proofed fiberboards and particleboards, plywood, isolation boards, and for the generation of wafer and oriented strand boards [24].

B. Wood–cement composites

Wood-cement composites have widely been used since more than 100 years ago. There are different definitions of wood-cement composites. Cement-bonded wood composites is a properly mixed strands, particles or fibers of wood using cement and fabricated into panels, bricks, tiles and other products used in construction industries [82]. Wood-cement products are form of inorganic-bonded wood composites that have a mineral or mineral mix such as binder agents [81]. The integration of wood elements in the board will improve its mechanical property such as the brittle fracture strength of the matrix material while retaining the excellent fire resistance related to the matrix The composite is a rigid open cellular structure produced from strands of wood and bound with cement. Boards made of cement-bonded are used for various housing components in Europe and the United States due to the quite short time for housing assembly [81].

Increase in the demand for cement-bonded wood stands as a replacement to asbestos based materials has encouraged researchers to study the use of abundant and cheap cellulosic residues [83]. The replacement of organic adhesives such as phenols and formaldehydes that is widely utilized in the production of particulated wood based materials with cement-bonded is a positive move in the right direction to produce safety and environmentally friendly products. Environmentally innocuous and cheap ceramic adhesives such as cement are of utmost priority. A good understanding of the mechanical and structural behavior of cement-bonded composites could enhance design and production of the composites and this will consequently reduce the cost. The stiffness and strength of the composite is a factor of the characteristics of wood and cement, the mineralization treatment of the wood, the density or compactness degree of the material and the wood–cement ratio [84, 85].

C. Merits of wood–cement composites

The cement-bonded composites possess excellent mechanical, physical, chemical and biological characteristics [81]. Some of the positive attributes are: low density, high durability, dimensional stability, fire and water resistance, good acoustic and thermal insulation properties, resistance to biological and environmental degradation, low production costs and the possibility to easily vary their characteristics base on specific needs are some of the most appreciated features of wood cement composites [86, 87].Other advantageous properties are stability, nailability, relatively light weight, sound attenuation and ability to provide a non-toxic shield against decay and termites (unlike resin-bonded particleboard). Also, the products lend themselves to modular construction; they satisfy the cultural preference for cement-based construction materials in many parts of the world, particularly in the tropics; and their manufacturing processes usually meet health and safety requirements [53]. Based on the physical and mechanical properties of cement- bonded particleboards, they are recommended for use, both indoor and outdoor application of a building such as wall surfaces and decking [85]. The production of particle from cement-bonded wood had low length swelling [18]. The weight of sawdust-cement particleboards is heavier than the particleboards produced with organic-bonded particleboards.

D. Demerits of biomass in cement and concrete composites

A wide range of agricultural wastes have been researched for construction and building material applications. Agricultural wastes show huge potential as cheap and renewable materialable to contribute to save conventional resources [42]. Short term characteristics of biomass cementitious materials are promising, more studies is require to enhance long service life of engineering performance of composites. There is paucity of information on long-term durability of biomass-based composites [42]. The major challenge on the use of biomass in a building material is the durability of plant parts in the cementitious matrix due to its alkaline properties such as calcium hydroxide[31]. The hydration taken place when there is a reaction between cement and water. Biomass comprises of cellulose, hemicellulose, lignin and other extractives. Alkalis have little effects on lignin at low concentration and ambient temperature but reacted with extractives and hemicellulose.

Types of cement-bonded wood composites

Wood-cement composites can be grouped into two categories namely:

i. The wood particle-cement composites
ii. Wood fiber-reinforced cement products

The wood particles or fibers mixed with cement to form wood-cement products should not of necessity be a solid wood. Recycling of agricultural and industrial residues based products can be a large source of fibers.

V. CEMENT-WOOD PARTICLEBOARDS

A. *Cement-Wood Ratios in Production of Particleboards*

There is paucity information on the properties of wood-cement composite boards. The condition and types of wood used in wood-cement mixtures have significant effect on setting time or complete setting failure of cement [88]. Different types of treatments and additives, especially hot-water extraction of the wood and calcium chloride additive to the cement have been found to reduce the setting time of wood cement mixtures [88].It has been observed that wood-cement composite board produced from wood slivers, sawdust, and cement have higher mechanical strength when the cement/wood ratio were increased from 3/4 to 3/2 [22].

B. *Effect of Addition of Calcium chloride ($CaCl_2$) in Cement-bonded Particleboards*

The mechanical and physical properties of bamboo-cement boards with inclusion of $CaCl_2$ (0%, 2% and 4%) showed significant difference as shown in Table 4. It was reported that the addition of $CaCl_2$ increases the moisture content [89]. The moisture content increased from 7.92% in bamboo-cement with 0% $CaCl_2$ to 10.5% in bamboo-cement with 4% of $CaCl_2$ as presented in Table 5. This could be attributed to hygroscopic character of $CaCl_2$. Calcium chloride is a deliquescent substance with strong affinity for moisture. When it is exposed, it absorbs relatively high amounts of water from the atmosphere thereby forming a liquid solution. The thickness swelling of in 2 hours for particleboard produced with addition of 4% of $CaCl_2$ was 30.4% higher than particleboards without the chemical additive [89]. There was no significant important after 24 hours in the thickness swelling. The addition of $CaCl_2$ reduced the water absorption, is an indication that the hygroscopic characteristic of $CaCl_2$ is more prominent on thickness swelling.

Cement-wood composites made with Eucalyptus urophylla and 4% of $CaCl_2$ as additive, revealed similar values with those from bamboo composites. The use of chemical additives such as calcium chloride ($CaCl_2$) in the production of cement-bonded particle board composed of *Haveabrasiliensis*, *Cupressusspp*. Or *Carpinusbetulus* L. enhances the inhibition index (I<10)[90]. The mechanical property using different wood-cement composites have shown that both bending strength and stiffness increase with increasing density of the material.

TABLE 4. Estimated Mechanical Properties of Bamboo-Cement Boards

Treatment	Modulus of elasticity (Nmm^{-2})	Modulus of rupture (Nmm^{-2})	Internal bonding strength (Nmm^{-2})	Dynamic modulus of elasticity (Nmm^{-2})
Bamboo 0% $CaCl_2$	3.083[a]	7.66[a]	0.21[a]	4518[a]
Bamboo 2% $CaCl_2$	3.114[a]	7.91[a]	0.28[b]	4.484[a]
Bamboo 4% $CaCl_2$	3.022[a]	7.36[a]	0.31[c]	4.339[a]
Structural board type HZ	3.000	9.0	0.40	-

Souece: Bison [91] and De Araújo et al. [92]

TABLE 5. Physical Properties of Bamboo-Cement Boards

Treatment	Moisture content (%)	Thickness Swelling (%)		Water Absorption (%)		Density (gcm^{-3})
		2h	24h	2h	24h	
Bamboo 0% $CaCl_2$	7.92[a]	0.92[a]	0.94[a]	4518[a]	20.70	1.18[a]

Bamboo 2% $CaCl_2$	9.88[b]	0.78[a]	0.87[b]	4.484[a]	19.61	1.22[b]
Bamboo 4% $CaCl_2$	10.50[c]	1.20[b]	0.92[c]	4.339[a]	19.28	1.24[c]
Structural board type HZ	9.0	0.8-1.3	1.2- 1.8	-	-	1.20

Source: Bison [91] andAraújo et al. [92]

VI. CEMENT-WOOD PARTICLEBOARDS

A. Common Uses OF Particleboards

Wang *et al*.[2] found that particleboards give domestic and industrial users the consistent quality and design flexibility to improve the quality of consumer products. Particleboard panels are produced in different dimensions. According to Wang *et al*.[2] and Faria *et al*. [90] particleboards have been found to useful in office and residential furniture, soundproof, home decking, ceiling, roofing, shuttering, cabinets, partitioning, prefabricated houses, cladding stair treads, underlaying floor, table, shelving, store fixtures, counter and desktops, office dividers, wall bracing, ceiling boarding, home constructions, sliding doors, kitchen worktops, interior signs, exam pad, photo lamination, low cost cabins peaker box, bulletin boards, packing boxes, thermal insulation and other industrial products. Particleboards are comprises of a kind of wood such as Pinuspinaster and/or Pinuspinea, Portland cement, sodium silicate and aluminum sulphate.

B. Factors Affecting Properties of Particleboards

There are many factors affecting the characteristics of the particleboards and the most prominent among them are species of wood, fibre structure, density, hardness, compressibility, type and size of particles and technique of particle drying [93]. Other factors include particle screening and separation, particle size distribution, type and amount of binding agents, method of mat formation, structure of particleboard, moistening of particles prior to pressing, final moisture content of board, conditioning, curing conditions, thickness of board[94]. Based on the findings of different researchers that worked on production of wood-cement boards reported the following factors affect the properties of wood-cement particleboards. These are ratio of cement to wood particles, ratio of water to cement and wood particles, type of cement, type and dimensions of wood particles, accelerator substance and curing time ([85].

C. Physical and Mechanical Properties of Particleboards

Wood-cement bonded particleboards have shown to be durable as well as cheaper [54]. Olorunnisola and Adefisan [63] reported production of particleboards, using mixture of sawdust from pine (*Pinuscaribaea* M) and coconut husk (*Cocosnucifera* L.). These particleboards were investigated for physical and mechanical properties such as thickness swelling, dry modulus of rupture and elasticity and density. The strength and density of wood –cement bonded particleboard improved with increased in quantity of cement. The obtained result revealed that the values of thickness swelling of the produced samples of the particleboard were lower than standardized 12% recommended by Yang *et al*. [95]. The thickness swelling of wood-based particleboard and palm kernel shell-wood based particleboard obtained after being soaked in water for 2 hours were 10.75% and 9%, respectively while their thickness swelling after being soaked in water for 24hrs were 11.75% and 10.25%, respectively. Table 6 presents the physical and mechanical properties of various fibres and plant-based fibre-like pieces. Density of the biomass ranged from 1.30 to 2.55 (g/cc). The highest tensile strength and Young modulus corresponded to carbon.

TABLE 6. Physical and Mechanical Properties of various Fibres and Plant-Based fibre-like Pieces

Biomass	Density (g/cc)	Extension at break (%)	Tensile strength (MPa)	Young's modulus (GPa)
Aramide	1.4–1.45	3.3–3.7	3000–3150	63.0–67.0
Carbon	1.40–1.75	1.4–1.8	4000	230.0–240.0
E-class	2.50–2.55	2.5	2000–3500	73.0
Cotton	1.50–1.60	2.0–10.0	287–597	5.5–12.6
Flax	1.40–1.50	2.7–3.2	343–1035	27–80
Hemp	1.40–1.50	1.3–4.7	580–1110	3–90
Jute	1.30–1.50	1.4–3.1	187–773	3–55
Sisal	1.30–1.50	2.0–2.9	507–855	9.0–28.0

Source: Batra[96]

D. Water resistance capacity of cement-bonded particleboards

Water resistance capacity of cement-bonded particleboards increased with increase in cement content. The water absorption of the boards is significantly affected by type of wood particle used, wood/cement ratio and chemical additives. The chemical additive played has an inhibitory role in the water absorption capacity of the boards. The chemical additives had significantly influenced on the water absorption capacity of the particleboards. The inverse relationship is always observed between wood/cement ratio and the water absorption capacity of the particleboard [55].

The thickness swelling of the boards is significantly influenced by wood/cement ratio and chemical additive. Asasutjarit et al. [54] observed that $CaCl_2$ treated composites generally absorbed less water at 2 h and 24 h respectively, than the untreated ones. This is could be attributed to changes in the fiber structure that made them stiffer and tougher by attaining high cement-to-cement bonds and cement-wood bonds. The average water absorption in most of the boards was less than 20% at 2 h, and less than 29% at 24 h of immersion in water. The corresponding water absorption in the neat cement at 2 and 24 h respectively, were 10.7 and 15.6%. It is a confirmation that lignocellulosics generally tends to increase the hygroscopicity of cement-bonded composites [25]. The observed water absorption values compare favorably with the findings of previous studies [54-56]. According to Ashori *et al*. [25], this could be attributed to the hydrogen bonding of the water molecules to the free hydroxyl groups in the cellulosic cell wall of woody material and the diffusion of water molecules into the wood–cement interface. Additionally, large number of porous tubular structures present in wood structure can hasten the absorption of water by the capillary action. After the saturation of cell wall, water occupies micro void spaces. Olorunnisola [93] reported that materials like wood can be incorporated in cement-bonded composites if the products are to be used for interior applications. However, such composites should be kept under pressure after production until curing is nearly complete.

E. Thermal and sound properties of particleboards

The particleboards produced from waste wood also revealed outstanding structure-borne noise reduction (at 32–100 Hz) and low thermal conductivity (0.29Wm^{-1} K^{-1}) (Table 7). This is an indication that particleboard has potential application as acoustic and thermal insulating materials. Preliminary cost-benefit analysis showed economic viability of the proposed approach. The scanning degrees ranged from 0º to 60 º 2h with 5 º min^{-1} at 45 kV and 200 mA. The crystallization enthalpy (100 ºC –1100 ºC) was evaluated by conducting thermo-gravimetric analysis of the particleboards. The thermo-gravimetric analysis of particleboards from waste wood showed a substantial weight loss at 270–350 ºC. The magnitude was positively related with wood content and sign of wood decomposition. This temperature range was more than the ignition point (190–260 ºC) reported for wood. This is an indication that wood particles in enmeshed in the cement hydrates improved the fire resistance of particleboards to some extent [87].

The effect noise reduction efficiencies of particleboards produced from waste wood were investigated at low-to-medium noise frequency (i.e., 32–3150 Hz). The particleboards showed better noise insulation effectiveness than concrete boards at almost all frequency ranges. Even though waste wood itself was most effective for noise reduction at higher noise frequency, the waste wood particleboards showed outstanding noise insulation at a low sound frequency (32–100 Hz), in which the emission of structure-borne noise (i.e., 32–100 Hz) normally originates from vibrating room boundaries [95].

TABLE 7. Thermal Conductivity and Density of different Boards

Types of boards	Thermal conductivity $Wm^{-1} K^{-1}$
Wood particleboard	0.29 ± 0.01
Concrete board	1.52 ± 0.03
Waste wood	0.07 ± 0.00

Source: Wang et al. [87]

F. Particleboards Produced from Sawdust and Palm kernel shells

Traditionally, particleboard is produced from wood-based fibers bonded together using a binder such as formaldehyde resin forming a tight compact panel that can be machined. The expected thickness is obtained by using a hot press that forms the particleboard into sheets [15]. Particleboard as a homogenous structure that can be formed in various sizes, thickness, densities and grades for different uses. Wang et al. [2] reported the production of particleboard by spraying wood particles with adhesive, forming them into a mat, and compressing the mat to desired thickness between heated platens to cure the adhesive. Most times, particleboards are of three layered board, with fine particles on the top and bottom surfaces while larger sized wood flakes are found in the middle. Particleboard and fiberboard are particle composites that are commonly known based on size of wood components and the techniques of production. Particleboards have chips, flakes, or wafers as the major constituent while the main constituents of fiberboards are fiber and fiber bundles [96]. The strength of the composite is dependent on binder, size and shape of the particles [15].

G. Pretreatment of Materials for Production of Cement-bonded Particleboards

Cement bonded particleboards are produced from cement, wood and some other additives. The mixture of cement, wood and water is achieved in the ratio of 3:1:1 of the respective constituents. The evaporation of water is monitored regularly and water should be added if necessary. Calcium chloride ($CaCl_2$) is added to the mixture to enhance the cement setting more rapidly. The mixture is then fed at a uniform rate into a conveyor driven series of caul plates moving at uniform speed. The mat is subsequently cut into desire lengths of the same size as the caul plates. These mats are stacked and compressed together to one third of its original height within three minute (3 min.). The mats are clamped and heated in a chamber at 70-80 ºC for 6-8 hours. The cauls plates are removed and the boards dried, trimmed and stored for 12-18 days for curing.

In spite of the excellent performance of cement bonded boards, many wood species and agricultural residues may not bond well with cement to form suitable panel due the presence of some chemical substances in the wood which hinder the proper setting of the cement binder [95. Majority of these lignocellulosic materials contained compounds of soluble sugars and wood extractives. These substances hinder cement hydration such as hardening and setting thus hindering the cement crystalline formation essential for strength. The adoptions of various pretreatment techniques have made possible the utilization of a wider variety of wood-based materials for cement particleboard production. Some studies have been conducted on minimizing inhibitory effects of some agricultural and industrial wastes with the use of calcium chloride ($CaCl_2$) as an accelerator [97]. It was found that calcium chloride has some effects on the bending elasticity, compressive strength and sorption characteristics of cement bonded particleboard products [53, 85]. More studies and information is required on the strength, stiffness and sorption of cement bonded particleboard to enhance their acceptance and use, both in the outdoor and indoor structural applications. Table 8 and 9 showed the suitability of some biomass for the production of particleboards. It is imperative to testing whether the wood species and agricultural wastes significantly enhance the physical and mechanical properties of boards.

TABLE 8. Inhibitor Index to Classify Wood–Cement Compatibility.

Inhibitory index (%)	Grade
1 < 10	Low inhibition
I0< 1<50	Moderate inhibition
50<1<100	High inhibition
I > 100	Extreme inhibition

Source: Okino et al.[18] and Ashori et al.[85]

TABLE 9: Inhibitory Index of some Wood Species.

Wood species	Inhibitory index (%)
Beech	57.1
Hornbeam	52.2
Pine	39.1
Maple	22.2
Fir	16.5
Birch	11.5
Poplar	7.4

Source; Ashori et al. [85]

G. Physical, Mechanical and Thermal Conductivity Properties of Sawdust and Palm kernel shells

The physical properties of the sawdust and palm kernel shell are summarized in Table 10. Bulk density and specific gravity of sawdust and palm kernel shell are 288 Kg/m^3 and 560 Kg/m^3, 1.38 and 1.26 respectively [28]. Fono-Tamo*et al.* [28] reported some physical and mechanical properties of sawdust based particleboard at moisture content 11.89% are presented in Table 11.Table12 reveals the mechanical and thermal conductivity properties of sawdust-PKS based particleboard are presented in Table 12. The result of physical, mechanical and thermal conductivity revealed in Table 11 and Table 12 were significant different. Plate 3 shows sawdust-palm kernel shell based particleboard.

TABLE 10: Physical Properties of Sawdust and Palm kernel Shells (PKS)

Test	Sawdust	PKS Particles
Bulk density (Kg/m^3)	288	560
Specific gravity	1.38	1.26

Source: Fono-Tamo et al. [28]

TABLE 11. Physical and Mechanical Properties of Sawdust based Particleboard

Tests	Sawdust based
Modulus of rupture, MOR (MPa)	5.654
Modulus of Elasticity, MOE (MPa)	2.454
Stress at proportional limit (MPa)	0.7524
Work at maximum load, (J)	7.14242
Air dried density, (g/cm^3)	0.54
Moisture content, MC (%)	11.89
Internal bond strength, IB (MPa)	3.770
Thermal conductivity, *k* (W/mK)	0.13
Thickness swelling, TS (%)	11.75

Source: Fono-Tamo*et al*. [28]

TABLE12: Physical and Mechanical Properties of Sawdust-PKS based Particleboard

Tests	Sawdust-PKS based
Modulus of rupture, MOR (MPa)	2.557
Modulus of Elasticity, MOE (MPa)	4.093
Stress at proportional limit (MPa)	0.50459
Work at maximum load, (J)	5.74691

Air dried density, (g/cm^3)	0.72
Moisture content, MC (%)	10.50
Internal bond strength, IB (MPa)	1.705
Thermal conductivity, *k* (W/mK)	0.5
Thickness swelling, TS (%)	10.25

Source: Fono-Tamo et al. [28]

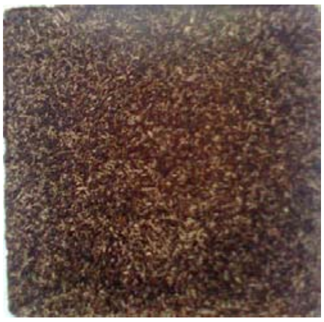

Plate1: Sawdust-palm kernel shell based particleboard
Source: Fono-Tamo et al. [28]

H. Electrical properties of particleboard produced from sawdust and palm kernel shells

Particleboard produced from sawdust and palm kernel shells was investigated for the electrical insulating properties [98]. It was found that electrical insulating characteristics of the particleboard improved with increased in palm kernel shells. It was observed that the particleboard with optimum electrical insulating properties is the one that corresponded to constituent composition of 50%:50% (sawdust::palm kernel shells) with an insulating resistance of 490 MΩ. The particleboard produced was good electrical insulator and reliable as well as safe for use to a maximum of 2500V [98].

VI. CONCLUSION AND RECOMMENDATION

The kind of particle used, wood-cement ratio and chemical additives have a significant influence on the physical and mechanical properties of the particleboards. The cement-bonded particleboards produced from of industrial and agricultural wastes were reviewed. The following conclusions were drawn. The increase in cement content of the boards and introduction of chemical additives lowers the water absorption and thickness swelling of the boards. Increase in cement content of the boards, pretreatment of lignocellulosic materials and addition of chemical additives significantly influence the particleboard density, internal bonding strength, modulus of rupture, modulus of elasticity, water absorption capacity and compressive strength of the particleboard. The modulus of rupture and modulus of elasticity significantly increase when boards are soaked in water, and untreated cement setting accelerators reduce the loss of modulus of rupture or modulus of elasticity. There is always inverse relationship between wood or agricultural waste/cement ratio and the water absorption capacity of the particleboards. The thickness swelling of the boards is significantly influenced by wood/cement ratio and chemical additive.

The review suggests the use of sawdust and agricultural wastes for cement-bonded particleboards but with inclusion of chemical additive for better physical, mechanical thermal and electrical properties. Also, the study suggests the pretreatment of the agricultural wastes with hot water at 80 ºC for shortening the setting time of wood cement mixtures.

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